

INTERIM REPORT

Sediment Volume Search Sonar Development (Phase II)

SERDP Project MR-2545

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Daniel C. Brown
Cale F. Brownstead
Shawn F. Johnson
**Applied Research Laboratory,
The Pennsylvania State University**

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14. ABSTRACT The objective of the Sediment Volume Search Sonar (SVSS) program is to improve buried unexploded ordnance (UXO) detection and classification performance over that which is available with existing systems. This objective is accomplished through the design, build, and demonstration of a sonar system for shallow-draft surface vessels. This sonar system is capable of producing a novel form of three-dimensional synthetic aperture sonar (SAS) imagery of surficial and buried UXO across a range of environments, and is particularly suited for use in water depths less than 3 m.					
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List of Acronyms

AAF	Auto-ambiguity Function
APL-UW	Applied Physics Laboratory at the University of Washington
ARL/PSU	Applied Research Laboratory at the Pennsylvania State University
ARL:UT	Applied Research Laboratory at the University of Texas
ASASIN	Advanced Synthetic Aperture Sonar Imaging Engine
ATF	Anechoic Test Facility
CUDA	Compute Unified Device Architecture
DRC	Dynamic Range Compression
DVL	Doppler Velocity Log
FFVS	Free Field Voltage Sensitivity
GPS	Global Positioning System
GPU	Graphics Processing Unit
GTRI	Georgia Tech Research Institute
HDF5	Hierarchical Data Format version 5
ITC	International Transducer Corporation
LOA	Letter of Authorization
MIP	Maximum Intensity Projection
PADCNR	Pennsylvania Department of Conservation and Natural Resources
PADEP	Pennsylvania Department of Environmental Protection
PFBC	Pennsylvania Fish and Boat Commission
PoSSM	Point-based Sonar Scattering Model
PPT	Part Per Thousand
RMSE	Root Mean Square Error
RTK	Real Time Kinematic
SAS	Synthetic Aperture Sonar
SBAS	Satellite-based Augmentation Service
SEDA-COG	Susquehanna Economic Development Association – Council of Governments
SVSS	Sediment Volume Search Sonar
TIER	Target in the Environment Response
TVR	Transmit Voltage Response
USACE	US Army Corps of Engineers
USGS	United States Geological Survey
UXO	Unexploded Ordnance
VAA3d	3D Visualization-Assisted Analysis

Keywords

underwater munitions, acoustic scattering, backprojection, beamforming, imaging

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1 Objective and Overview

The objective of the Sediment Volume Search Sonar (SVSS) program is to improve buried unexploded ordnance (UXO) detection and classification performance over that which is available with existing systems. This objective is accomplished through the design, build, and demonstration of a sonar system for shallow-draft surface vessels. This sonar system is capable of producing a novel form of three-dimensional synthetic aperture sonar (SAS) imagery of surficial and buried UXO across a range of environments, and is particularly suited for use in water depths less than 3 m. In addition to the fabrication of the sonar system, this program develops the necessary beamforming software for the production of three-dimensional SAS volumetric imagery and visualization software for the analysis of this unique imagery. Sufficient detection and classification performance is demonstrated to allow the operator to find surficial and buried objects of interest in water less than 5 m depth.

The SVSS program is divided into three sequential phases. The first phase consists of modeling and simulation of the SVSS sensor and its expected performance. This phase of the program was completed in early 2017 and the results were documented in a technical report [1]. This initial phase was followed by a design/build/demonstrate phase which focused on providing a demonstration of the advantages of the system design while using existing sonar hardware and software to minimize development costs. This technical report serves to document the results from that second, prototype demonstration phase. The third and final phase will focus on improving the system performance with purpose-built hardware design.

In the following section, the technical approach to Phase 2 of the program is provided. Section 2.1 will give a short overview of the acoustic environmental model developed under Phase 1, and updates occurring during the Phase 2 period which will be leveraged for future work. In Section 2.2, the hardware development and integration efforts are detailed. Section 2.3 describes improvements to the signal processing algorithms used to form three-dimensional imagery. The combined hardware and algorithmic system was used in a demonstration conducted at a test site installed at the Foster Joseph Sayers Reservoir. The selection of this test site and the installation of the target field are described in Section 2.4.

Testing results are provided in Section 3. Details are provided on selection of the transmit waveform in Section 3.1. Sonar imaging results from a high-frequency sidescan and low-frequency volumetric beamforming are provided in Section 3.2. Finally, since remediation activities typically require accurate localization of the imaged targets, the system localization accuracy is characterized by comparing absolute position estimates between a pair of data collections separated by eight days in Section 3.3.

This technical report is associated with a Go/No-Go decision point. The key questions and topics ARL/PSU has addressed with respect to this decision point are:

- characterization of target detection across a range of water and sediment burial

depths,

- demonstration of methods for mitigation of multipath reverberation,
- characterization of target localization accuracy,
- mitigation of the effects of platform motion on system performance, and
- mitigation of the effects of variability in sediment properties on performance.

Each of these items are addressed in this report, and the results of this analysis indicate that the SVSS design is capable of creating sub-bottom imagery of UXO in the test environment. Surficial and buried targets are successfully imaged across a pair of water depths and a range of burial depths. These targets are accurately localized by the sensor, and multipath interference is mitigated through sensor design. This technical report demonstrates that the prototype SVSS design provides a capability not found in existing systems.

2 Technical Approach

The goal of the second phase of the SVSS program is to demonstrate, using a prototype SVSS design, the capacity for the detection of buried UXO. The prototype system is based on significant leveraging of existing sonar hardware and software. Modifications made to this hardware were guided, in part, by the modeling and simulation results from the Phase 1. A brief summary of the continued development of these models is provided in Section 2.1. The development of hardware, and in particular a new projector, is detailed in Section 2.2. The signal processing algorithms used to convert the raw sonar data into three-dimensional imagery were also advanced during this phase. This work is described in Section 2.3. Finally, a test site was established for the demonstration of the SVSS. A description of the site and the targets installed is presented in Section 2.4.

2.1 Modeling Development

The Point-based Sonar Scattering Model (PoSSM) received considerable advancement under the initial phase of this project. These advancements enabled PoSSM to generate representative time series for the environmental component of the expected SVSS signal, and to use the APL-UW Target in the Environment Response (TIER) model to generate the target component. Together, these two models formed the basis upon which Phase 2 design decisions were made. A short description of PoSSM, including Phase 1 developments, will be provided here as background, with additional details available in the SVSS Phase 1 technical report [1]. Also presented here is a brief summary of developments made under collaborative projects, which we expect will be of significant benefit to SVSS for future model/data comparisons, and to guide future programmatic decisions.

2.1.1 PoSSM Summary

PoSSM is a sonar modeling tool which produces calibrated, bistatic, frequency-dependent, element-level, representative time series suitable for coherent signal processing. It employs a “model of models” architecture (Figure 1), with many of the acoustic sub-models already documented in peer-reviewed literature and textbooks. In this context, the term “points” is in reference to the discretization of the environment for calculation of the acoustic field via a variety of acoustic models (Figures 2 & 3). This architecture lends itself nicely for parallel computation, particularly on Graphics Processing Units (GPUs), with portions of the code implemented in CUDA, an application programming interface developed by Nvidia for execution on CUDA-enabled GPUs. The main development language for PoSSM is MATLAB. This combination allows PoSSM simulations to include millions of scatterer calculations on consumer-grade GPUs, to billions on server-grade GPUs, in a few seconds, while still retaining flexibility to implement or develop any necessary physics-based models. During Phase 1, modules for generating synthetic time series for diffuse interface scattering, specular interface scattering, and diffuse volume scattering

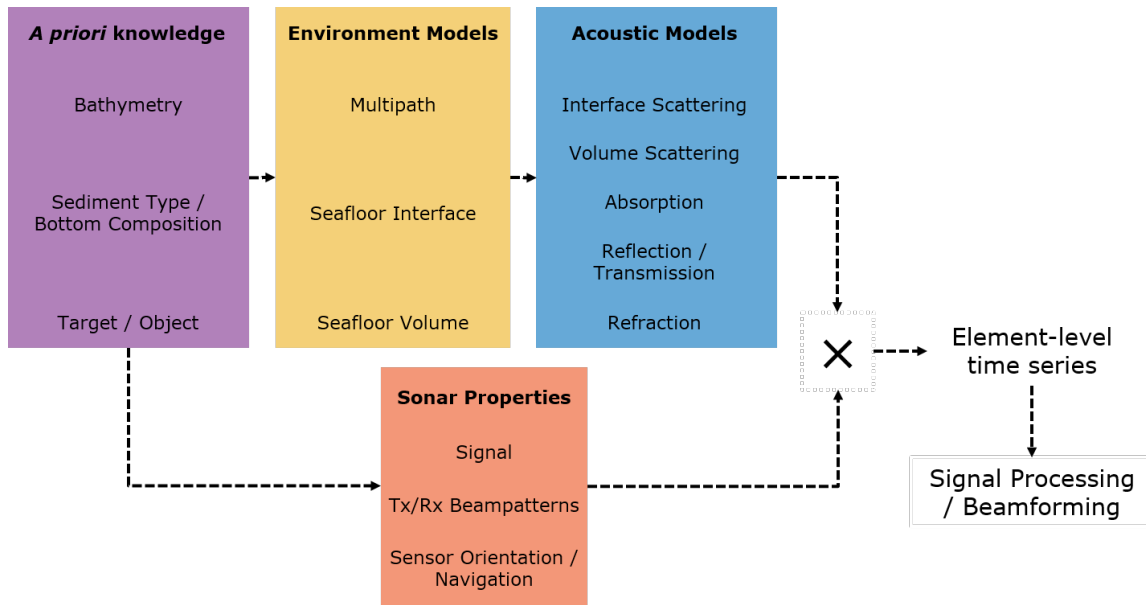


Figure 1: Flowchart of the primary constituents of the ARL/PSU Point-based Sonar Scattering Model (PoSSM).

were advanced, with the diffuse interface scattering component having been validated and documented in the literature [2].

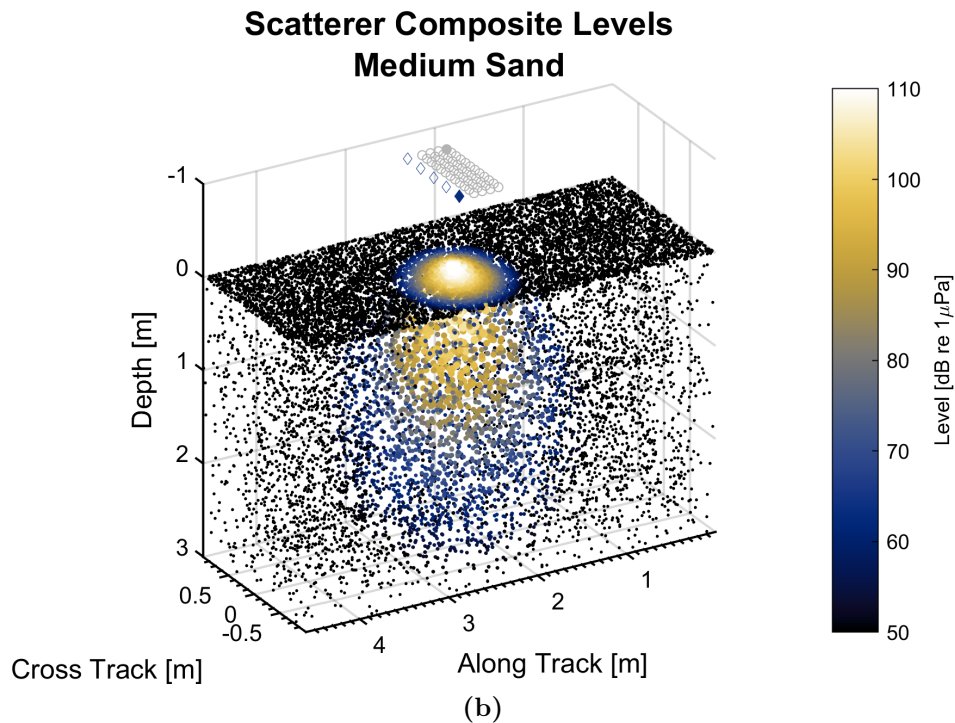
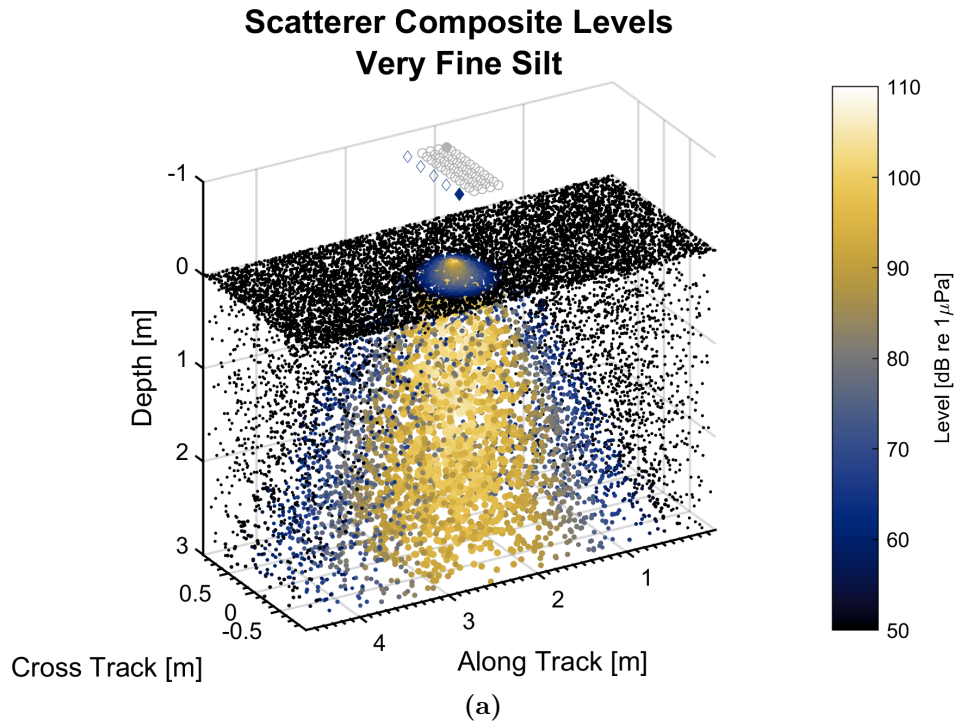


Figure 2: Diffuse interface and volume scatterer composite levels are shown for a single ping, between a single transmit-receive pair at the extreme corners of the sonar. The composite scatterer level includes the source level and effects of transmit and receive beampatterns, model-based scattering strength, attenuation, spreading loss, and, for volume scatterers, the two-way transmission through the interface.

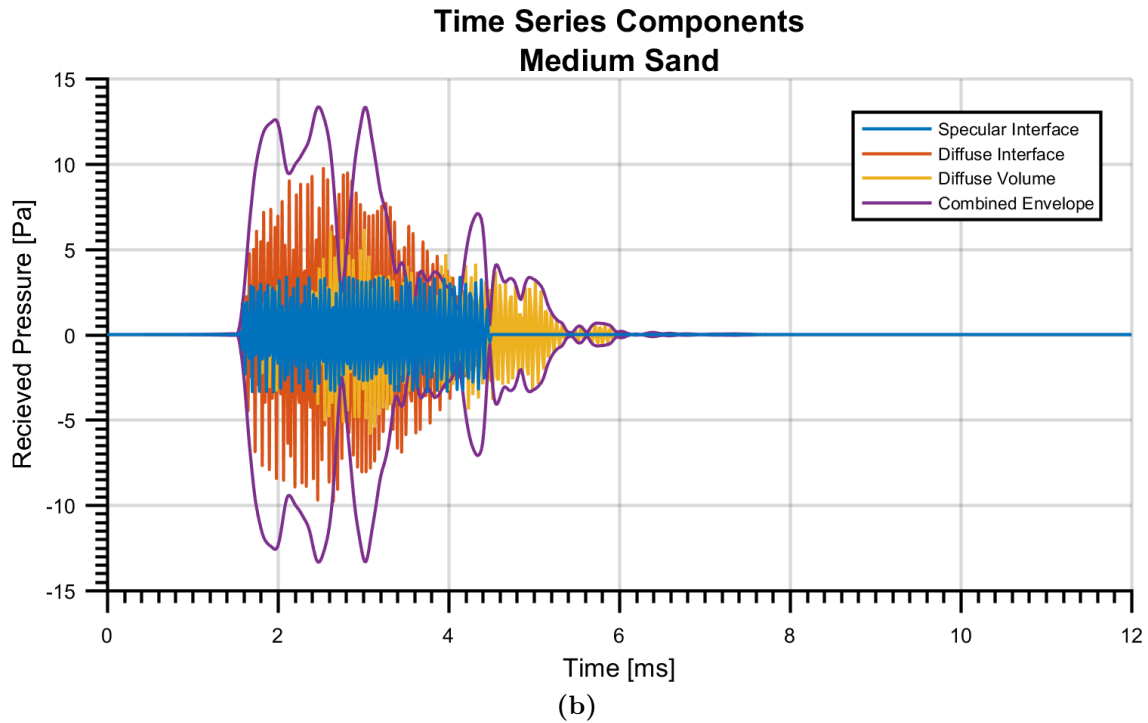
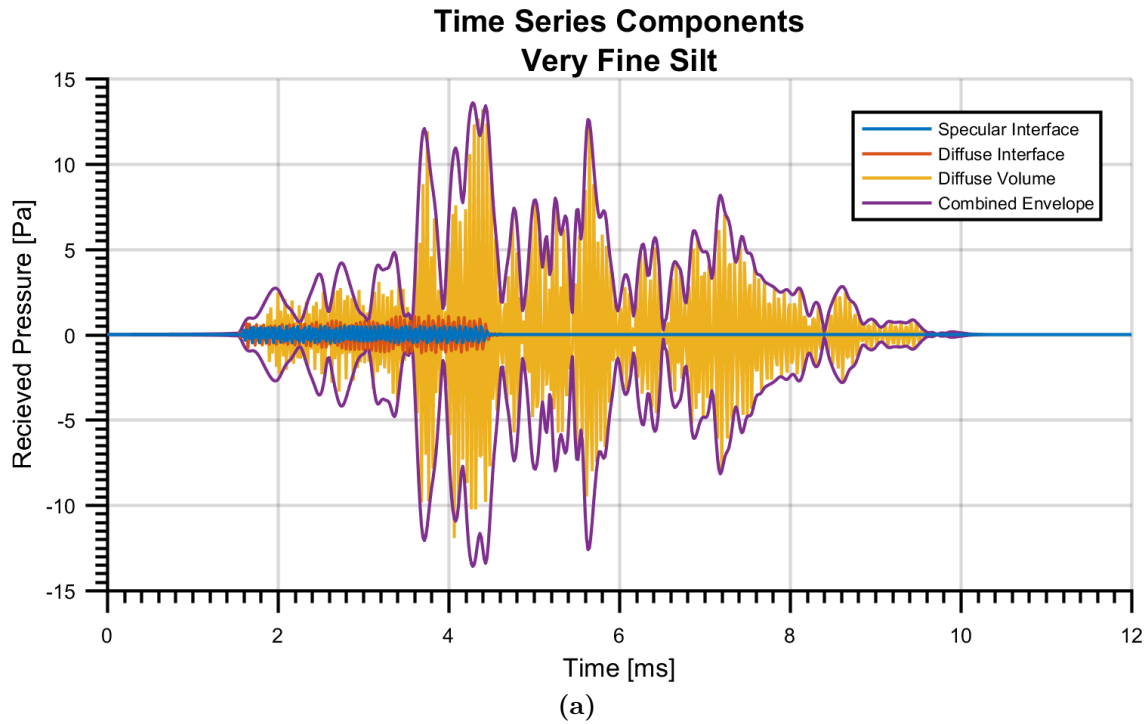


Figure 3: Simulated received pressure time series corresponding to Figure 2. The transmitted signal was a 15-25 kHz 3 ms LFM. For the Very Fine Silt simulation, the diffuse volume scattering component dominates the combined signal, whereas the diffuse interface scattering component dominates for Medium Sand.

2.1.2 Recent PoSSM Development

Since the completion of the Phase 1 technical report, PoSSM has received significant interest from the community and investment from other sponsors. Several advances we expect will be of benefit to SVSS are summarized in this section.

- **Development of Sediment-Sediment Layer Interface Component**

During Phase 1, development of PoSSM was focused on acoustic returns from the water-sediment interface, and the sediment halfspace. Upon further investigation of the test site at Foster Joseph Sayers Reservoir, the lakebed may be more closely approximated as a silty-clay sediment, deposited since reservoir creation, over top of an existing clay. Recent work has been conducted to permit calculation of the diffuse interface component from a sediment-sediment layer. Also, sediment properties utilized in PoSSM were based upon those described in APL-UW TR-9407 [3], which may not accurately represent the acoustic scattering, sound speed, and attenuation properties of the test site sediment. Recent improvements now permit more generic sediment types, for example values obtained from core logging. Future SVSS investigations may leverage these new PoSSM components to better represent the sediment at the current, and any future, test sites.

- **Seafloor Texture and Bathymetry**

To more appropriately simulate the diffuse interface component, the ability to account for seafloor texture and bathymetry has been included. While accounting for a non-flat seafloor is of greater importance to side-looking sonars at low grazing angles than to sonars operating at near-normal incidence when considering just the amplitude of the signal (since the effects of roughness are already included in the diffuse and specular interface level calculations), there may be some benefit to include roughness and bathymetry for quantifying SVSS beamforming performance over a varying bottom.

- **Generic Sonar Formats**

The sonar configuration has been generalized to allow PoSSM to simulate a wider range of sonar array designs. This is expected to benefit SVSS should a redesign feasibility study need to be conducted for future performance improvements.

- **General Efficiency and Stability Improvements**

As with any software-based product, there have been continual computational efficiency improvements, and corrections to inadvertent mistakes. There has been additional focus to ensure computational stability on any CUDA-enabled GPU. This includes ongoing strides towards establishing benchmark examples, as well as expanding from high-end consumer GPUs in workstations to both mobile workstation laptops with Nvidia GPUs and distributed computing systems. Work in this area is aimed at making PoSSM a capable tool for anything from basic research pursuits to large data generation tasks.



Figure 4: The Sound Hunter test platform is a nine-meter pontoon boat. The projector and receive array are shown here mounted in the forward portion of the boat. These components are mounted in a rectangular frame that is lowered into the water during testing.

2.2 Hardware Development

The modeling and simulation effort described in the SVSS Phase 1 technical report explored a notional design of a two-dimensional synthetic aperture sonar system [1]. This design involved leveraging existing hydrophone modules and developing a new acoustic projector. As part of the Phase 2 effort, the hydrophone array was expanded to 80 channels and reconfigured into a geometry suitable for sub-bottom imaging.

The boat and the SVSS sonar hardware configuration are shown in Figure 4. In the forward portion of the boat, the sonar transmit and receive hardware is seen mounted in a rectangular frame with several yellow cables. A schematic diagram of the projectors and receivers is shown in Figure 5a and a photo of the array mounting plate is shown in Figure 5b. The receiver locations are shown as small yellow squares with the letter R, and the projectors are shown as larger blue squares with TX and a subscript to indicate the position. The projector labeled TX_F is unused for the SVSS program. Finally, a Doppler Velocity Log (DVL) is mounted in the aft portion of the plate, and it is shown with an orange circle.

The SVSS receive array is made up of a series of eight-channel hydrophone modules. These modules are designed so that when flush mounted they create arrays with a 9.14 cm center-to-center spacing. In the modeling and simulation phase, the array was made up of six

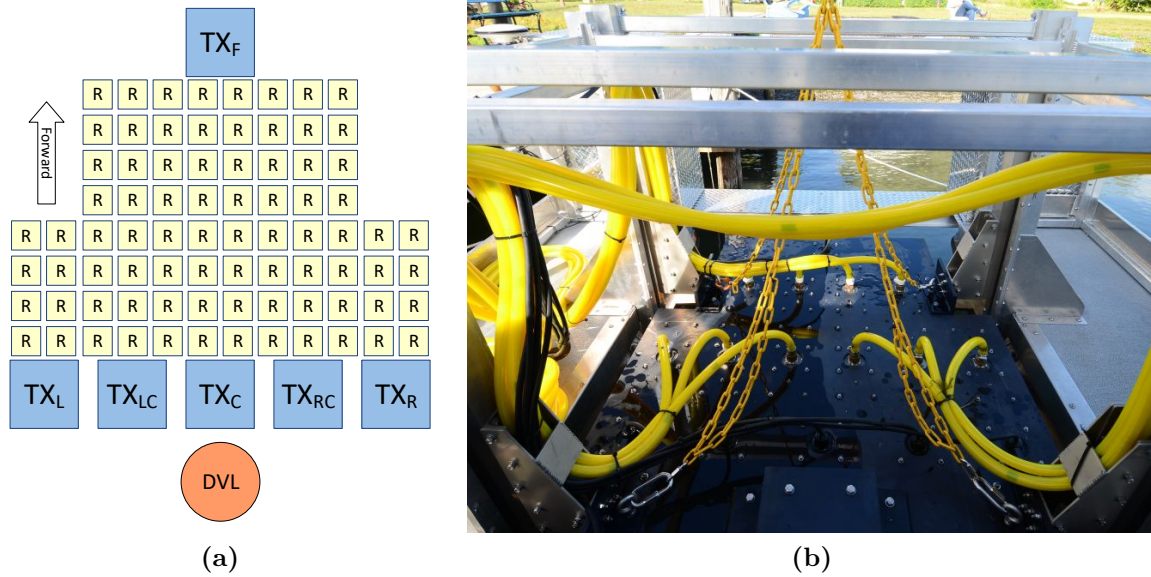


Figure 5: A schematic diagram and photo of the Sound Hunter array configuration are shown in (a) and (b), respectively. The array consists of 80 receive channels, which are labeled R, and six projectors, which are labeled TX_{XX} . The SVSS can also utilize a Doppler Velocity Log (DVL) which is mounted aft of the sonar array.

of these eight-channel modules and they were arranged in a 4x12 channel grid. Four new hydrophone modules were fabricated during Phase 2 and the array was expanded to add a 4x8 channel section forward of the originally planned 4x12 channel section. This layout is seen in Figure 5a. In this arrangement, the sonar array will be roughly 73 cm in the along-track direction and 1.1 m in the cross-track direction.

2.2.1 Projector Development

Sediment interface and volume reverberation are the dominant sources of interference in the detection of buried UXO. Minimizing this reverberation requires highly directive transmit and receive beams; however, a highly directive real aperture projector can only interrogate the small region ensonified by its beam. This greatly restricts the area coverage rate of such a system. To avoid this limitation in the SVSS, transmit directivity will be achieved in post-processing by using the coherent combination of a series of transmissions from broadbeam projectors. This is equivalent to the approach used by a synthetic aperture sonar to synthesize large transmit and receive apertures to achieve high resolution imagery. Using the array configuration shown in Figure 5, the projectors are ensonified in a repeating sequence (TX_L - TX_{LC} - TX_C - TX_{RC} - TX_R) as the sonar system transits a survey track. This will permit SAS beamforming in both the along-track and cross-track directions independently. Performance gains of this design are described in detail in the Phase 1 technical report [1].

After the Phase 1 modeling and simulation effort, the goal was to identify a low-cost, commercially available transmit element, and build a suitable mounting baffle to produce the desired beam width and passive multipath rejection. The intended benefit of this approach was to keep the production cost of a final system as low as possible. The ITC-1001 transducer, which was manufactured by International Transducer Corporation (ITC), was modeled along with a number of baffle designs. Validation of this modeling effort was to be followed up with tank experiments for characterizing baffle performance. Unfortunately, ITC declared bankruptcy during the execution of Phase 1, and ceased production of transducers. ARL/PSU reached out to additional vendors; however, it was not possible to identify any commercially available transducers that could meet our schedule and/or technical requirements.

As a fallback plan, ARL/PSU decided to build a custom projector based on an existing tonpilz transducer element [4]. These tonpilz elements are surplus items, and were provided to this program at no cost. A tonpilz projector is typically built from an array of tonpilz elements mounted in an air-backed housing. While the design of this housing adds additional design cost, it does have one distinct advantage: the housing's air-filled back volume creates a significant baffling effect that limits the sensitivity of the projector in the aft direction. For the current use case (downlooking), this design reduces multipath interference by attenuating the transmitted field in the direction of the air-water interface.

The tonpilz elements are connected to a mount, or “web”, within the housing. The design of the web must provide the proper element location and spacing to achieve the desired beampattern from the active face of the transducer. It must also provide acoustic isolation of the elements from the non-active surfaces of the housing and between each other. This acoustic isolation is critical to reduce unwanted radiation that may contribute to multipath interference.

The transducer element has a nodal attachment to the mount. This type of attachment assumes that the transducer element mounting plate is located at a minimum displacement location in the ceramic motor section, or a node. This does not mean zero displacement. As such, when the transducer is driven to produce sound from the radiating head, it must react against the mounting location. In order to reduce the amount of vibration from the nodal drive point that reaches the array housing, there must be an additional amount of isolation provided between it and the transducer elements. The mount design is a layered damping media with metallic constraining septum concept. The forward septum provides a rigid mounting surface for element alignment in the array. The middle layers consist of polyurethane and corprene (cork/rubber). The aft septum acts as a rigid mounting surface for the array housing and a reflective layer in the impedance mismatch. Corprene, whose characteristic impedance is five times lower than water/urethane, also provides isolation primarily through impedance mismatch. The SVSS projector design arrangement is shown in Figure 6. It should be noted that while this design is relatively inexpensive and effective, it can only be used in low hydrostatic pressure (i.e. shallow water) conditions.

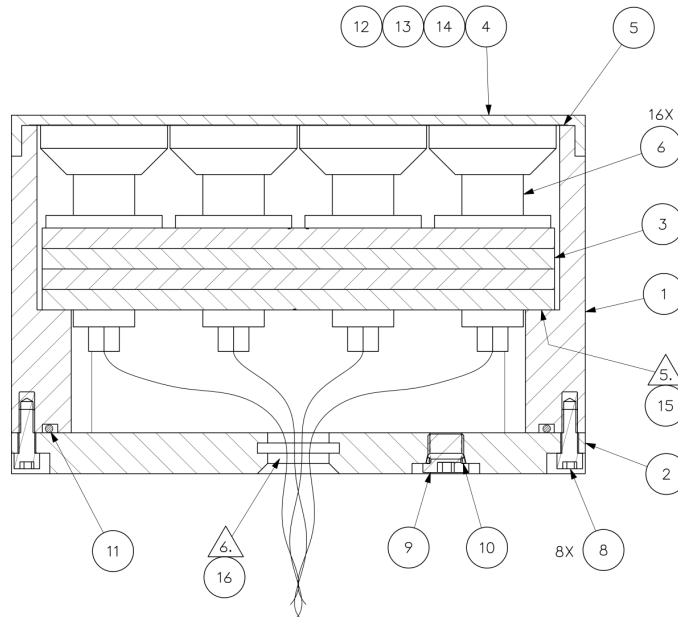


Figure 6: Cross section of projector array, mount, and housing. A tonpilz element is called out as item 6, and the layered mount which provides element isolation is called out as item 3.

The utility of the above design is best seen by reviewing the actual directivity of the final array assembly. A transmit directivity pattern is shown in Figure 7. The front-to-back ratio of the sound is > 30 dB and the sidelobe levels are < -20 dB. The implication of this performance is that the isolation system is working to both minimize the vibration from the projector elements getting to the housing, and to reduce the element-to-element interaction to the point that it is not elevating the sidelobe energy. Since the corners of this unit are shaded, the aperture acts like a circular piston which should have at least -17.8 dB secondary lobes, relative to the main lobe of the pattern at 20 kHz. Additionally, the modeled sensitivity of the projector is compared to the measured sensitivity in Figure 8. At the 100 V full drive voltage, this projector is capable of a peak source level of 200 dB re μPa @ 1 m.

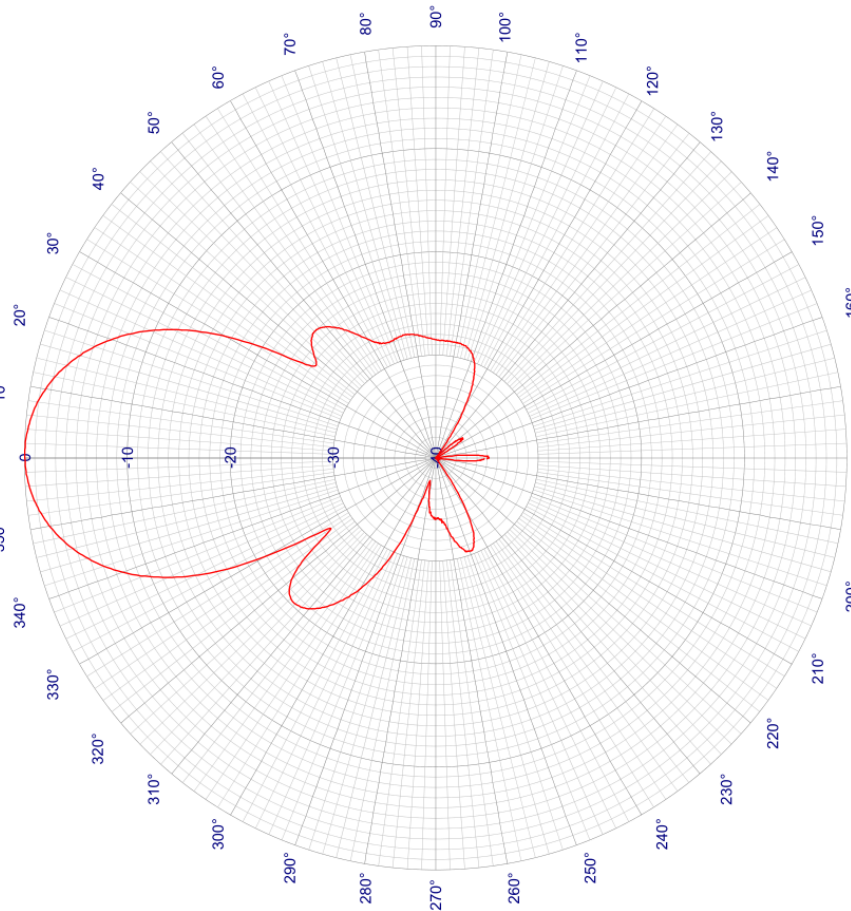


Date: 8/24/2017
Time: 2:41:55 PM

TVR (dB re 1µPa/V @ 1m)	
Property	Value
Peak Level (dB)	159.93
Peak Angle (deg)	0.39
Pattern Index (dB)	17.04
3 dB Beamwidth (deg)	26.92
6 db Beamwidth (deg)	37.4
10 dB Beamwidth (deg)	47.04
Max SideLobe Lvl (dB)	-20.29

Frequency: 20 kHz
Roll Plane: 0 deg

SVSS Projector SN 001
L6 Amplifier



ARL/PSU Anechoic Test Facility

Figure 7: Projector directivity pattern at 20 kHz.

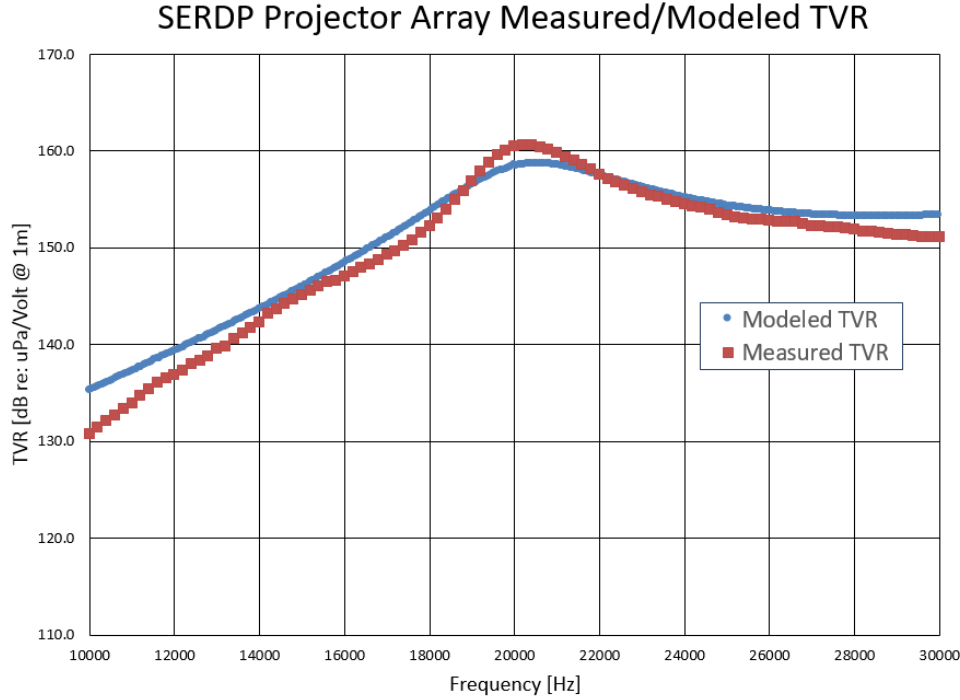


Figure 8: The modeled Transmit Voltage Response (TVR) of the 16 element projector design is compared to the measured TVR.

2.3 Signal Processing Algorithm Development

The raw data generated by the SVSS sensor must be processed in order to form three-dimensional imagery of the seafloor volume. The process of converting from raw, channel-level measurements of the scattered pressure field to an image is called beamforming. A number of beamforming algorithms have been developed in numerous research areas including radar imaging [5], seismic imaging [6], and sonar imaging [7]. One technique that is known for its combination of simplicity and robustness is the backprojection beamformer [8]. This class of beamformer is also commonly known as a “time-domain” beamformer.

The central concept in backprojection is an inversion of the forward propagation and scattering model through time-domain manipulations of the recorded signals. This inversion is performed in order to form an estimate of the scattering strength of the scene that has been ensonified. Using the geometry defined in Figure 9, the value written to a pixel at a position $\bar{\chi}_S$ is given by

$$f(\bar{\chi}_S) \propto \iint_{-\infty}^{\infty} w(\bar{\chi}_T, \bar{\chi}_R, \bar{\chi}_S) p(\bar{\chi}_T, \bar{\chi}_R, t) \delta\left(t - \frac{c}{2}(|\bar{\chi}_S - \bar{\chi}_T| + |\bar{\chi}_S - \bar{\chi}_R|)\right) d\bar{\chi}_S \quad (1)$$

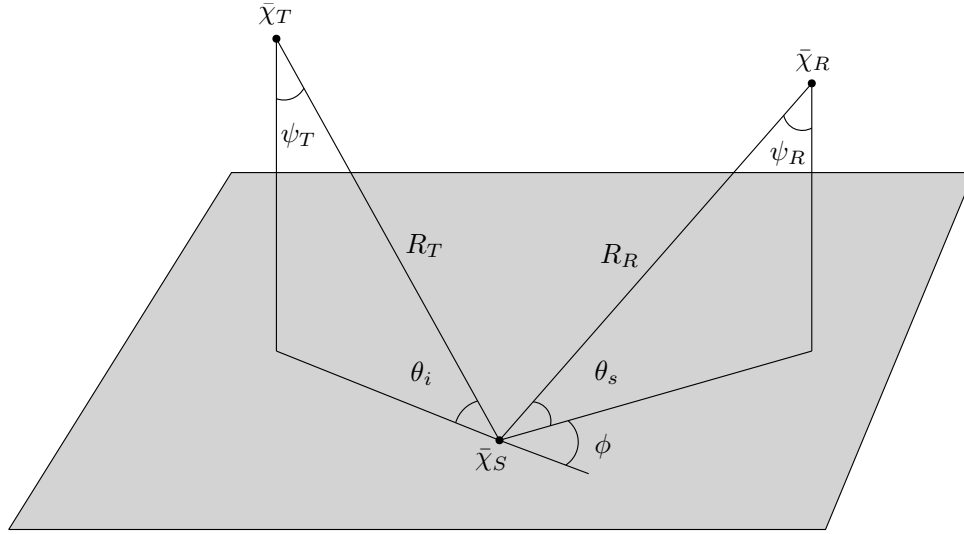


Figure 9: The field projected by a transmitter at $\bar{\chi}_T$ is scattered from an interface point at $\bar{\chi}_S$ and is received at $\bar{\chi}_R$.

where δ is the Dirac delta function, $p(\bar{\chi}_T, \bar{\chi}_R, t)$ is the scattered field observed at the specified positions, and $w(\bar{\chi}_S)$ is a weighting function applied to the aperture.

When compared to other beamforming techniques, the backprojection algorithm has a relatively intuitive interpretation. Equation 1 states that every beamformed pixel consists of the accumulation of a number of weighted and delayed time series; hence, the backprojection algorithm is often described as a “delay-and-sum” beamformer.

ARL’s implementation of a backprojection beamformer is called the Advanced Synthetic Aperture Sonar Imaging Engine (ASASIN) [9]. ASASIN was originally implemented to generate high-resolution synthetic aperture sonar (SAS) imagery from both high-frequency (>100 kHz) and mid-frequency (~ 10 kHz) imaging sonar systems. Each of the imaging sonar systems supported by ASASIN generate two-dimensional imagery from one dimensional receiver systems. Additionally, the region imaged on the seafloor is typically in the far-field of the physical sonar system. Neither of these are true for SVSS data; consequently, several changes were made during the first phase of the SVSS program to adapt ASASIN to near-field volumetric beamforming. The primary changes were to:

1. calculate independent transmitter and receiver element field-of-view prior to back-projection,
2. include a sediment-water interface refraction model in determining propagation time, and
3. enable three-dimensional data output and provide three-dimensional image viewers.

Traditional SAS beamforming assumes an isovelocity (constant sound speed) propagation path between the sensor and the imaging point. While this isovelocity approximation is rarely true, small deviations in sound speed have a minor effect on image quality. In the

case of larger deviations, autofocus techniques may be applied to recover some loss of focus quality [10]. SVSS imaging within the seafloor may present the backprojection algorithm with a discontinuity in sound speed much greater than that ever observed for propagation in water. The effect of refraction must be included in the beamforming algorithm to give the best possible image quality. Fortunately, the backprojection algorithm is well suited to this type of modification. For any desired imaging point, one only has to provide a model for the propagation time from the source to the imaging point and from the imaging point back to the receiver. This model was implemented in ASASIN as a root solver during Phase 1. Extensive testing in Phase 2 revealed numerical instability for some imaging conditions. A new implementation of the of a (up to) fourth order root finding algorithm has been developed. Under some circumstances the condition of the system can become stiff or even ill-conditioned, which can adversely affect the accuracy of the computed roots. This new root finder overcomes some of the previous difficulties encountered with its predecessor which required special treatment in order to handle numerically challenging situations.

Several simplifications and approximations were used in the Phase 1 modeling and simulation effort. First, the sound speed was a user-specified parameter. ASASIN now calculates the sound speed for the SVSS from the recorded water temperature (and salinity if appropriate) using the Mackenzie equation [11]. Second, the altitude of the sensor above the interface was a user-specified parameter. ASASIN has been modified to include an altitude estimation algorithm prior to the beamforming stage. Finally, the modifications to the beamforming kernel implemented in Phase 1, while mathematically correct, were not optimized for speed or memory usage. The beamforming kernel within ASASIN was modified in numerous ways to address shortcomings in the Phase 1 implementation. Global memory management was improved, and a more efficient use of hardware registers resulted in increased performance.

The primary ASASIN output data type is called the Science product. The Science product is written using the open Hierarchical Data Format version 5 (HDF5) format [12]. It includes the complex output imagery, navigation information, environmental information, and system parameters. A detailed list of the data included in this format is provided in Table 1. A batch processing framework has also been established for post-processing the beamformed imagery. In this framework, a directory of output is recursively processed to generate data representations such as image slices or projections. These data products are discussed in Section 3.2.2. Where appropriate, these new output products can be georeferenced using the information provided in the /Geodesy/ group.

Table 1: ASASIN generates the Science data product which is an HDF5 file containing processed sonar imagery as well as information about the data collection and signal processing algorithms. The output stored in /Data/ has dimensions MxNxL where M is along-track, N is cross-track, and L is depth. The image is formed using P sequential transmissions (pings) of the sonar system. The version number in the final column indicates the science file version where each dataset was added to the format.

Dataset Name	Size	Type	Units	Version
/Version	1x1	Float64		1.0
/ASASIN	3x1	UInt32		1.0
/Band	1x1	Enumeration		1.0
/Side	1x1	Enumeration		1.0
/Data/Imag	MxNxL	Float32		1.0
/Data/Real	MxNxL	Float32		1.0
/Environment/Salinity	1x1	Float32	PPT	1.2
/Environment/SoundSpeed	1x1	Float32	meters/second	1.2
/Environment/Temperature	1x1	Float32	Celsius	1.2
/Geodesy/WGS84				1.1
/Geodesy/WGS84/CoordinateTransformation	4x4	Float64		1.1
/Metrics/DpcCorrelation	1x1	Float32		1.0
/Metrics/ImageQuality	1x1	UInt32		1.3
/Nav/Acceleration	Px3	Float64	meters/second ²	1.0
/Nav/Altitude	Px1	Float64	meters	1.0
/Nav/Course	1x1	Float64	radians	1.0
/Nav/Depth	Px1	Float64	meters	1.0
/Nav/Latitude	Px3	Float64	radians	1.0
/Nav/Longitude	Px1	Float64	radians	1.0
/Nav/Pitch	Px1	Float64	radians	1.0
/Nav/PitchRate	Px1	Float64	radians/second	1.0
/Nav/Position	Px3	Float64	meters	1.0
/Nav/Roll	Px1	Float64	radians	1.0
/Nav/RollRate	Px1	Float64	radians/second	1.0
/Nav/Time	Px1	Float64	seconds	1.0
/Nav/Velocity	Px3	Float64	meters/second	1.0
/Nav/Yaw	Px1	Float64	radians	1.0
/Nav/YawRate	Px1	Float64	radians/second	1.0
/Parameters/CenterFrequency	1x1	Float32	Hertz	1.0
/Parameters/CircleRadius	1x1	Float32	meters	1.0
/Parameters/IntermediateFrequency	1x1	Float32	Hertz	1.0
/Parameters/Pings	1x1	UInt32		1.0
/Parameters/PingsOverlap	1x1	UInt32		1.0
/Parameters/PingRange	1x2	UInt32		1.4
/Parameters/ResolutionAlongTrack	1x1	Float32	meters	1.0
/Parameters/ResolutionCrossTrack	1x1	Float32	meters	1.0
/Parameters/ResolutionDepth	1x1	Float32	meters	1.0
/Parameters/SystemSampleRate	1x1	Float32	Hertz	1.0
/Parameters/UpsampleFactor	1x1	UInt32		1.0

2.4 Test Field Installation

This section documents the installation of the SERDP test site at the Foster Joseph Sayers Reservoir. Section 2.4.1 provides an overview of the reservoir, details on sedimentation rates, a description of how the test area was selected, and the necessary approvals and permitting process to utilize this site. Section 2.4.2 reviews the target types, their burial locations, and photos of the individual objects.

2.4.1 Foster Joseph Sayers Reservoir

Foster Joseph Sayers Reservoir, near Howard, PA approximately 20 miles NNE of ARL/PSU, was created in 1971 by the United States Army Corps of Engineers for flood control. This lake covers roughly 1,700 acres and is eight miles in length. During the winter months, typically December to April, the pool height is lowered to accommodate springtime snow-pack runoff, which exposes a portion of the lakebed. The test site was chosen due to its close proximity to ARL/PSU, and because the winter lowered pool height provided a unique opportunity for establishing an accurate ground truth test bed. At low pool height during March 2017 and 2018, two testing sites were prepared, with sonar testing being conducted during the summer of 2017 at full pool height.

An image of the lake is provided in Figure 10. The lake was formed by damming Bald Eagle Creek. The creek inlet is seen in the southwest corner of the lake, and the dam is in the northeast corner. For flood control, the the US Army Corps of Engineers seasonally reduces the pool height by approximately 5 feet in early December, and another 10-15 feet in February. A historical plot of the lake level for a 16 month period is provided in Figure 11.

A detailed study of sedimentation within the lake was conducted by Flippo as part of Department of the Interior preparations for the construction of the dam [13]. This study estimated Bald Eagle Creek provides a suspended sediment load of 32,000 tons per year. The suspended sediment was found to be 34 percent clay and 62 percent silt, with the remaining sediment being sand. Flippo estimated that 70 percent of the transported sediment is deposited or trapped in the lake. This sedimentation rate represents 12 acre-feet of capacity loss per year. Assuming this sediment is uniformly spread over the reservoir, 2.1 mm of sediment will accumulate per year. Over the 47 years since the study, sedimentation should account for approximately 10 cm of accumulation. This agrees well with our observations of a 7-8 cm upper silt layer during the target field installation, Figure 12.

The approved testing area is approximately indicated with an orange box in Figure 10 and is also shown in more detail on a bathymetric chart in Figure 13. Two sub-regions were selected to install a pair of test fields. When the reservoir reaches the typical summer



Figure 10: The Foster Joseph Sayers Reservoir is located near Howard, PA and it serves as the site for SVSS testing and demonstration.

pool level, one of these sub-regions has a 1.3 m water depth, while the other has a 3.0 m water depth. The absolute depths vary slightly based on actual pool height. These sub-regions will be described as “shallow” and “deep,” respectively, for the remainder of this report.

The test area was selected based on an analysis of water depths, surface craft traffic patterns, and historical imagery. This section of the lake provides water depths that allow characterization of the shallow water imaging capability of the SVSS sensor. Due to the shallow water depths and the proximity of the partially exposed railroad bed to the northwest of the test areas, recreational boat traffic is relatively low. Finally, an analysis of historical imagery helped to identify sub-regions within this test area in which to establish the test sites. Four images of the test site, collected over a 76 year period, are shown in Figure 14. Figure 14a, which was taken in 1938, shows the fields, forest, and farm land that was in place before the dam was built in 1971. A farm field, visible as a white right-trapezoidal shape, provides an ideal location for planting the target field because land used for agricultural purposes will have had all tree stumps and large near-surface rocks removed. Figure 14b was taken as the area flooded after the dam was built. Figure 14c shows the lake level near the maximum winter drawdown, while Figure 14d

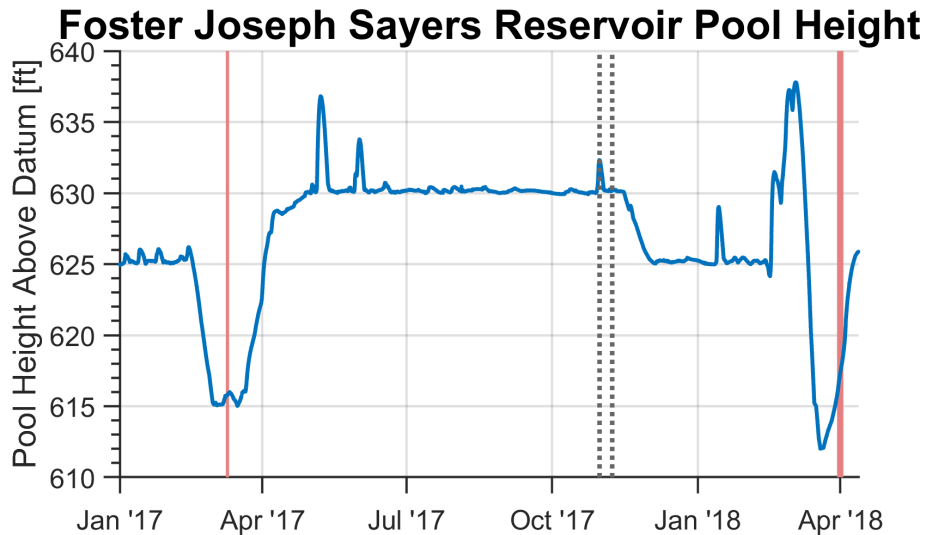


Figure 11: The reservoir level is varied throughout the year. Typical summer pool height is 630 ft, with two stages of drawdown during the winter for flood control: 625 ft and 615 ft. Red bands indicate test site preparation periods during 2017 and 2018 respectively, and gray dashed lines indicate the main two testing dates discussed here.

shows the lake at the full summer pool level. Additionally, the remnants of a road on the southwest edge of this field are still visible in Figure 14c. This road provides a firm bottom for staging equipment during test field installation.

ARL/PSU has been working with various federal and state organizations to obtain necessary permissions and to address concerns raised. To date, these discussions have included the US Army Corps of Engineers (USACE), the Pennsylvania Department of Conservation and Natural Resources (PADCNR), the Pennsylvania Fish and Boat Commission (PFCB), the Pennsylvania Department of Environmental Protection (PADEP), and the Susquehanna Economic Development Association Council of Governments (SEDA-COG) Joint Rail Authority. The essence of the permitting process seeks to ensure the safety of both researchers doing the testing and other users of the lake, and to abide by any pertinent environmental protection legislation.

To minimize impact to other users, a less trafficked region of the reservoir was chosen as the test site, and operations were conducted during the workweek. The permissions/permits ARL/PSU has obtained are summarized below.

- PADCNR Letter of Authorization

- Summary: The Letter of Authorization (LOA) provides permission for activities described in the LOA. A summary of activities, and time and location to conduct activities, are outlined in the document. A summary of the aforementioned items, including a Risk Management Plan and insurance rider, is required.

- Status: **Issued; LOA-0720 (2017), LOA-1979 (2018).**
- USACE Real Estate Permit
 - Summary: The Real Estate Permit allows for ARL/PSU researchers to access the test site from USACE land, which may be outside PADCNr jurisdiction, in order to bury the targets. Insurance rider is required.
 - Status: **Issued; License #DACW-31-3-17-0260.**
- PFCB Buoy Permit
 - Summary: A buoy permit allows ARL/PSU to place buoys as markers to identify the test field. This identification is meant to facilitate testing as well as mark a potential hazard to navigation (although none is expected since the targets will be buried).
 - Status: **Issued; Permit #1620.**
- SEDA-COG Private (RR) Grade Crossing
 - Summary: A private grade crossing allows ARL/PSU to have a temporary crossing installed across active railroad tracks to facilitate test site access for personnel and equipment during site preparation periods. Insurance rider is required.
 - Status: **Issued; License #00-132.0.**

ARL/PSU has received concurrence from both state and federal authorities that the planned scientific experiments are compliant with environmental protection legislation. Several key aspects of the planned experiment were highlighted as bringing the activities into compliance *without* the need for further approval:

1. objects being placed are for scientific purposes,
2. objects will be constructed of inert materials,
3. objects' positions will be recorded,
4. objects will be removed at the completion of the study, and
5. no additional sediment fill is required.

The relevant legislation and confirmation of compliance is summarized below.

- Pennsylvania State Environmental Protection Code (Title 25)
 - **Confirmed.** Email received 5 October 2016 from Kipp Starks (PADEP); SVSS activities qualify for Waiver 12 under Chapter 105 § 105.12(a)(12)
- United States Environmental Protection Agency Clean Water Act
 - **Confirmed.** Email received from Amy Elliott (USACE); Sec 404 states Federal authorization is assumed with State Waiver 12 (below)



Figure 12: The two distinct sediment sequences are visible in this photograph taken from within a test hole dug prior to target deployment. The uppermost sequence is made up of the fine silt and clay transported into the reservoir by Bald Eagle Creek.

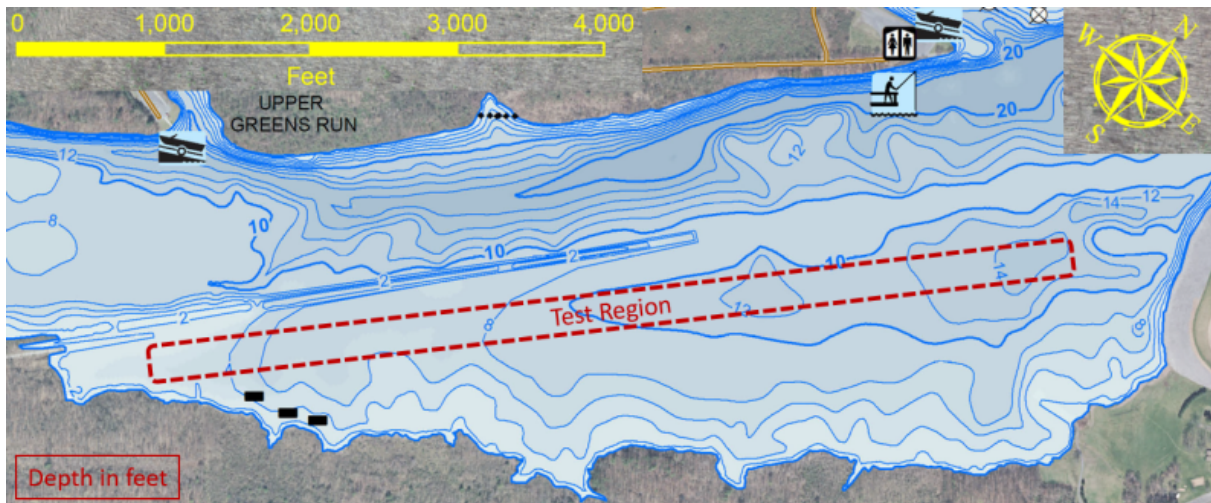


Figure 13: The region approved for testing is shown on a map of the lake depth. Note an old railroad bed to the north-west of the test region. This feature is visible in the aerial photos shown in Figure 14.

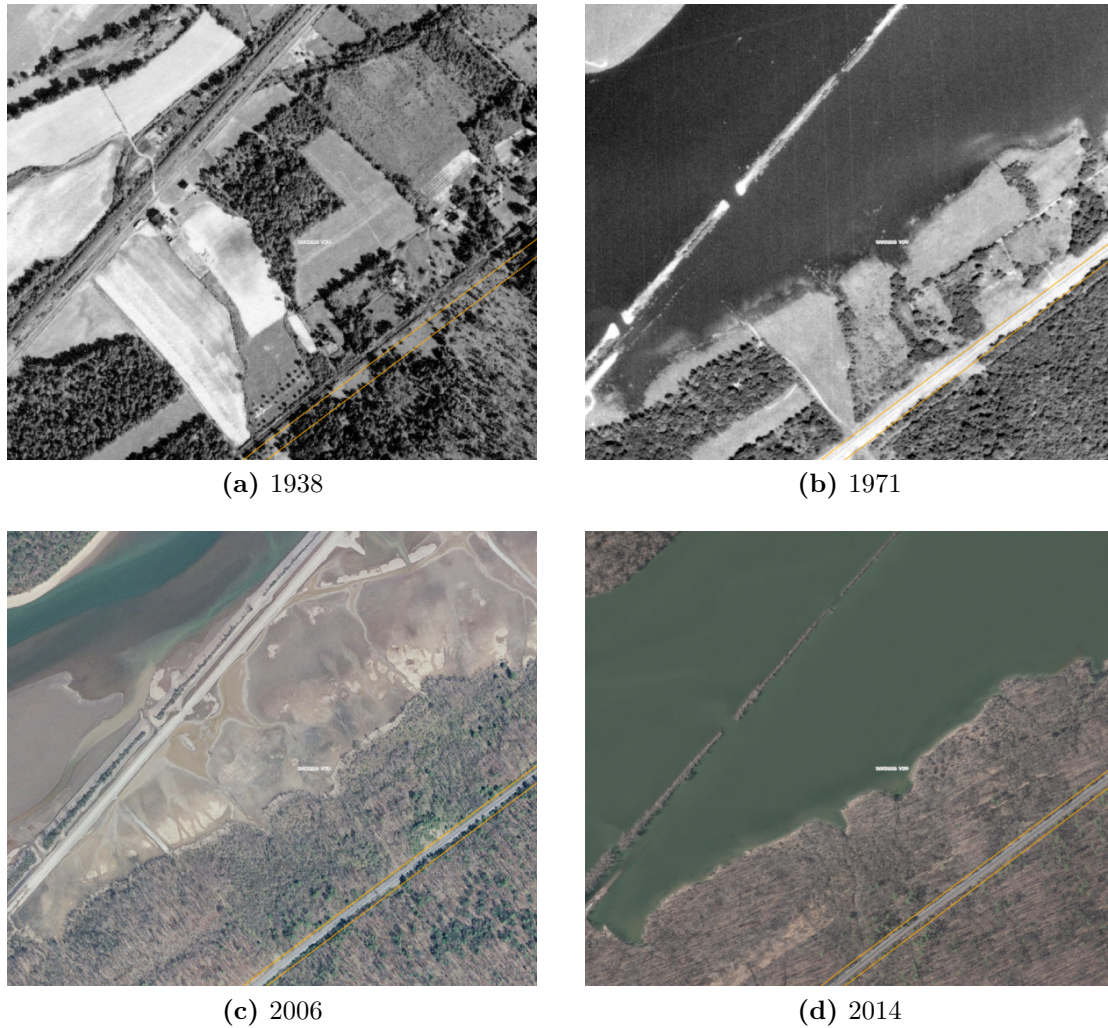


Figure 14: This figure provides a view of the region of Sayers Lake where the shallow test site is planned. In 14a a white farm field can be seen that has a right-trapezoidal shape. This farm field will provide an ideal location for planting the target field because land used for agricultural purposes will have had all tree stumps and large surficial rocks removed.

2.4.2 Target Deployment

An initial set of targets were deployed in early March of 2017. The installation process included one day of staging the targets and equipment along the exposed roadbed near the test sites. This staging exercise was followed by two days of target installation. A list of the deployed targets and their properties is provided in Table 2. The target strengths listed in this table are high frequency ($ka \gg 1$) approximations taken from Urick [14, Table 9.1]. These targets were selected to provide a range of sizes for evaluation of the SVSS while also being small enough to be manually transported 1.2 miles from the shore of the lake.

The final layouts for March 2017 installation of the shallow and deep sites are provided in Figure 15. The shallow site has fifteen target positions labeled P01-P15 in Figure 15a. At each of these positions, the target is indicated with the target identifiers from Table 2. The targets labeled “Tx” are a “mixed” target type. At shallow P14, a shot put is buried with a ladder section on the interface above it. At shallow P15, a shot put is buried with another shot put on the interface above it. Additionally, another ladder section is on the interface parallel to shallow P11. The deep site has thirteen target positions labeled P01-P13 in Figure 15b. Again, at each of these positions the target is indicated with the target identifiers from Table 2, and the targets labeled “Tx” are a “mixed” target type. At deep P11, two surface shot puts are closely spaced.

Table 2: Target properties for items deployed in the Sayers Reservoir shallow and deep fields during the 2017 test site installation.

Target Name	Target Identifier	Target Length [cm]	Target Diameter [cm]	Target Strength [dB]	Target Description
Shot put	T1	N/A	10.2	-31.9	12 pound steel shot puts
Small Cylinder	T2	30.5	15.2	-11.9	Solid Al (6061) cylinder
Large Cylinder	T3	61.0	15.2	-5.9	Solid Al (6061) cylinder
Concrete Block	T5	39.7	19.8	-	Cinder block
Clutter	C	Various	Various	-	Assorted rocks from area

After target deployment, aerial imagery of the test location was reviewed to ensure the surface targets had not been disturbed after deployment. A mosaic of the overhead imagery is shown in Figure 16. In this figure, the shallow and deep sites are called out by red boxes and associated labels. The submerged roadbed forms a vertical feature through the image. The white areas of the image are due to snow that fell shortly after deployment. Detailed imagery for the shallow site and deep site are shown in Figure 17. The concrete blocks marking the corners of the test field are seen in the corners of these figures. The surface targets are more easily visible against the background of sediment in

the deep site. The surface ladders are easily seen in the shallow site.

As each target was placed, it was photographed with a slate including the target identification and a handheld GPS unit to document the target position. Orientation was recorded for the cylindrical targets using the magnetic compass in the handheld GPS. Finally, the burial depth to the top of the target was recorded for each of the buried targets. Individual images of each placed target are shown in Figure 18 and 19.

Beneath each image in these figures is a unique target identification string. The string begins with {D,S} to indicate the shallow or deep site. This is followed by {P##} to indicate the position within that site. This is followed by {T#} to indicate the target type provided in Table 2. Finally, the identification string ends with {D#} to indicate the nominal burial depth. D0 targets are proud, D1 target are buried approximately 5 cm, and D2 targets are buried approximately 10 cm. Actual target burial depths determined by physical and acoustic survey are provided in Table 5.

For reference, a selection of the additional targets installed in the March 2018 field installation are provided in Figure 20. These new targets include several inert ordnance as well as additional clutter targets.

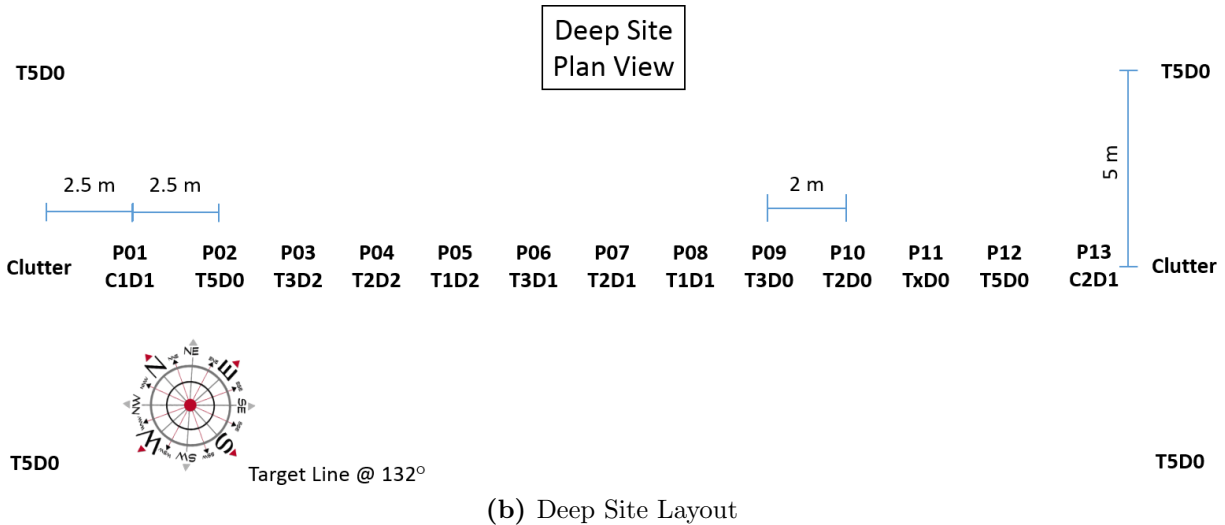
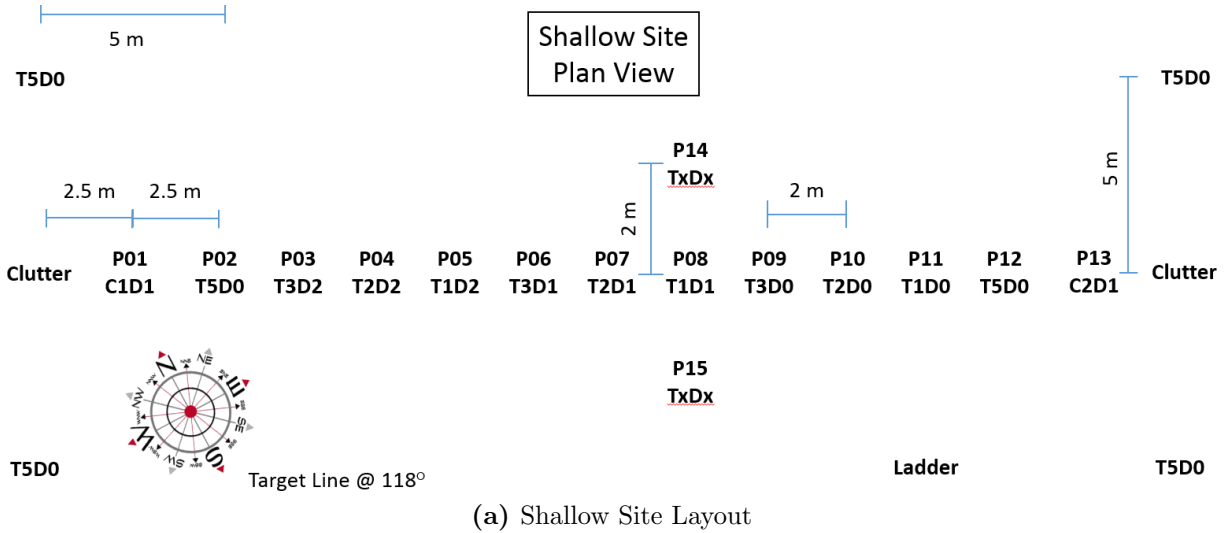


Figure 15: The shallow site and deep site target layouts are provided above. Note that the orientation of the layout is provided in the lower left corner of each figure. The shallow site has fifteen target positions (P01-P15), and the deep site has thirteen positions (P01-P13). The target type identifier is shown below each position, and the reference can be found in Table 2. Target positions specified with a target type “x” are mixed combinations of targets. See the text of the document for a description of these positions.



Figure 16: Aerial imagery collected in the days after the target field installation shows both the deep and shallow sites. This figure is oriented so that the submerged roadbed runs vertically. The white areas on the ground are the remnants of a snowfall that occurred shortly after deployment.

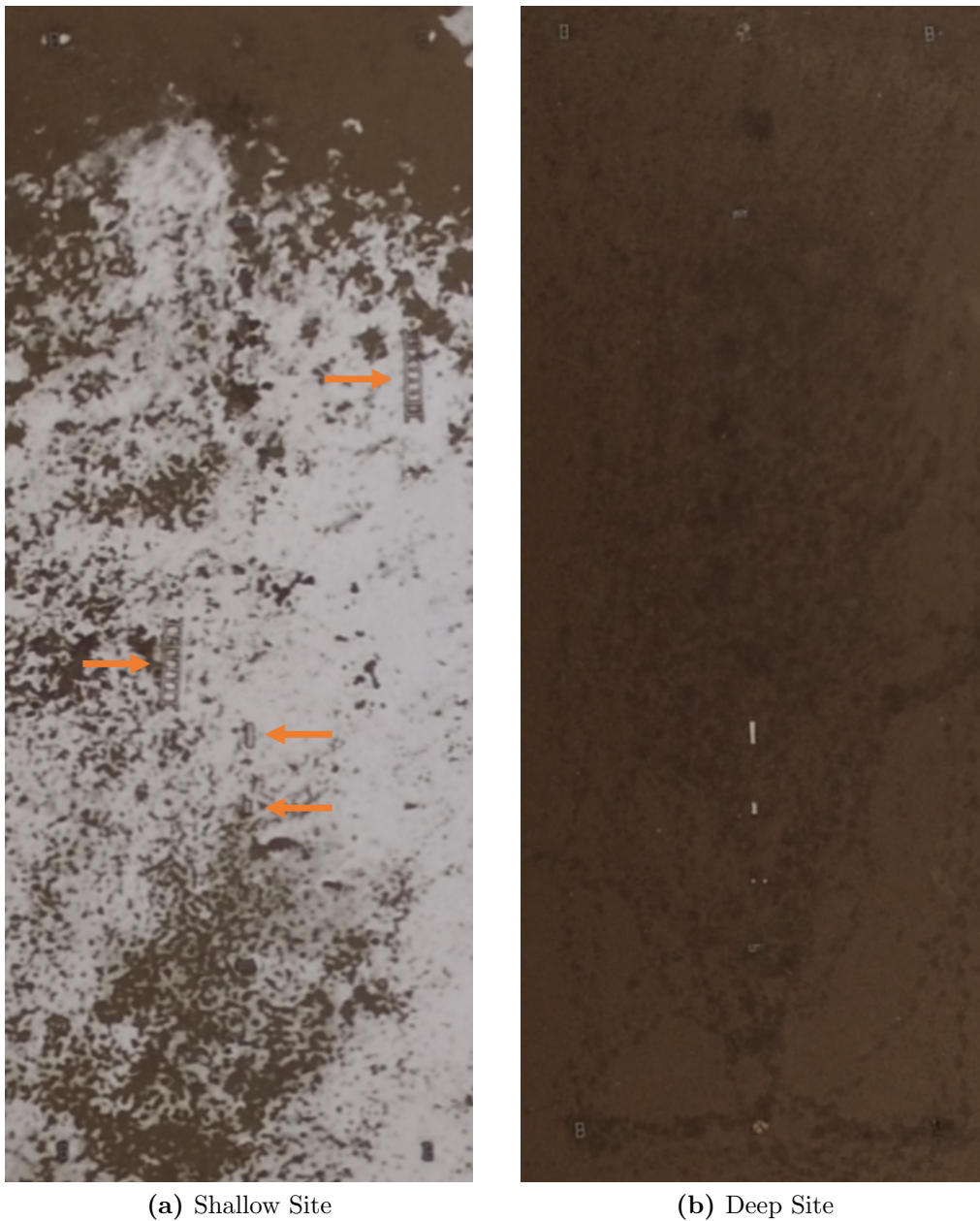


Figure 17: The test site details are provided from the mosaic shown in Figure 16. The shallow site (a) is partially obscured by snowfall. The ladders and surface cylinders are called out by arrows. The deep site (b) shows more detail due to the lack of snow. All of the surficial targets, markers, and clutter are visible here.



Figure 18: Shallow field targets.



Figure 19: Deep field targets.



Figure 20: New targets installed in the March 2018 deployment.

3 Results and Discussion

The SVSS system was tested at the Foster Joseph Sayers Reservoir test site seven times over a seven week period spanning 13Sep2017 – 8Nov2017. Testing dates and goals are provided in Table 3. Initial testing focused on troubleshooting and characterizing the installation of new sonar hardware. The proximity of the test site shortened the overall schedule during this debugging phase. Any problems identified during testing were addressed back at ARL/PSU facilities. Following successful hardware integration, testing was conducted to characterize a number of potential transmit waveforms. The waveform details are provided in Section 3.1. Using the identified waveforms, data were acquired during a pair of surveys on 31Oct2017 and 8Nov2017. The survey results for a commercial the high-frequency sidescan data are provided in Section 3.2.1. The results for the ARL-built low-frequency sub-bottom imaging are provided in Section 3.2.2.

For brevity, the characterization of the sensor hardware has been withheld from this section, and is instead presented in Appendix A. This appendix includes sensor noise characterization in Appendix A.1, projector calibration in Appendix A.2, and hydrophone calibration in Appendix A.3.

Table 3: Seven test events were held over the period spanning 13Sept2017 – 8Nov2017.

Test Date	Test Goals
13Sep2017	Self Noise Characterization & Projector Integration
15Sep2017	Electronic Self Noise Characterization & Troubleshooting
22Sep2017	Self Noise Characterization & Projector Integration
28Sep2017	Projector Testing
10Oct2017	Waveform Characterization
31Oct2017	Initial Survey
8Nov2017	Final Survey

3.1 Waveform Selection

A number of transmit waveforms were employed to characterize the SVSS projector performance. Seven distinct waveforms, whose properties are listed in Table 4, were used during these two events. There are several competing criteria to consider in the waveform selection process. Low frequencies are desired to minimize sediment attenuation and to potentially excite elastic phenomena within UXO. High bandwidth is desired to provide fine depth resolution in the output imagery. Finally, spectral windowing should be applied to the signal to insure the auto-ambiguity function (AAF) has low sidelobes. The quality factor of the projector at its 20 kHz resonance frequency created an artificially narrowband signal for those waveforms that swept through this frequency. In considering the 20-35 kHz waveforms, the shortest pulse length created lowest sidelobes in the AAF.

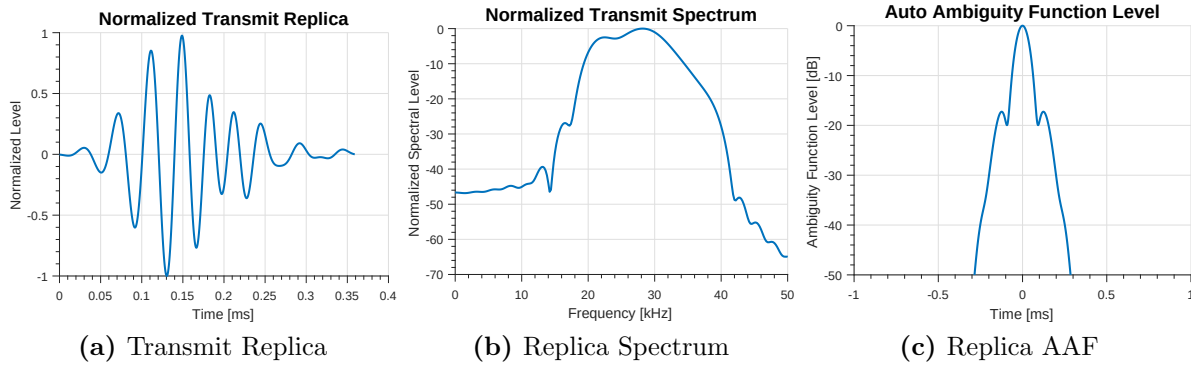


Figure 21: The primary waveform used during testing is a linearly frequency modulated chirp spanning 20-35 kHz with a pulse period of 257 μ s. A Taylor window, with 5 sidelobes at -40 dB, is applied to this transmit signal to reduce sidelobes in the auto-ambiguity function.

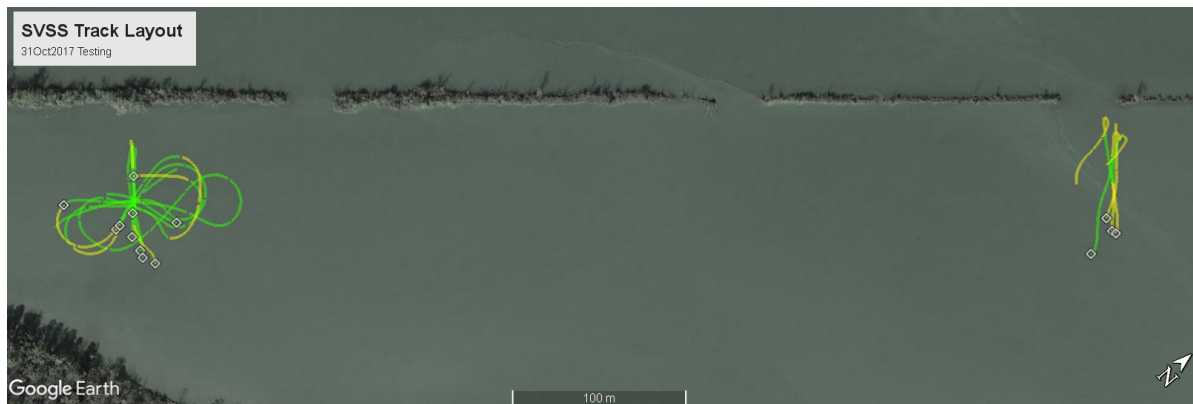
Consequently, the bulk of the testing conducted on 31Oct2017 and 8Nov2017 used the first waveform listed in Table 4. The normalized waveform, transmit spectrum, and AAF are plotted in Figure 21.

Table 4: Several waveform options were examined during testing. The first waveform in this table was selected for use in the majority of the testing conducted on 31Oct2017 and 8Nov2017.

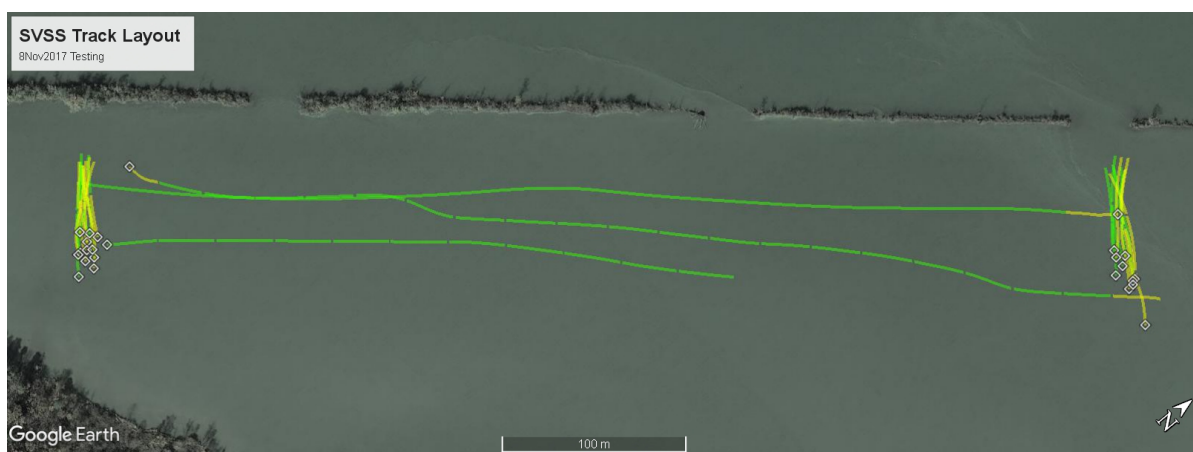
Waveform Type	Start-Stop Frequency [kHz]	Pulse Length [ms]	Window Type
LFM*	20-35	0.255	Taylor (5,-40 dB)
LFM	20-35	1.000	Taylor (5,-40 dB)
LFM	20-35	2.016	Taylor (5,-40 dB)
LFM	12-27	0.257	Taylor (5,-40 dB)
LFM	12-27	1.025	Taylor (5,-40 dB)
LFM	12-27	2.023	Taylor (5,-40 dB)
LFM	10-40	2.016	Chebyshev -100 dB

3.2 Sonar Imaging Results

The objective of the surveys conducted on 31Oct2017 and 8Nov2017 was to detect the presence of objects in the two target fields described in Section 2.4. The SVSS system tracks for the two survey days are shown in Figure 22. The testing on 31Oct2017 collected four tracks in the deep field and ten tracks in the shallow field. Testing on 8Nov2017 attempted to provide coverage over the test site by “mowing the lawn” with a series of nominally straight and parallel tracks. Fourteen tracks were collected in the deep field,



(a) 31Oct2017 Testing



(b) 8Nov2017 Testing

Figure 22: Georeferenced tracks are shown for survey testing on 31Oct2017 and 8Nov2017. The shallow and deep test sites are located on the left and right of this figure, respectively.

and twelve tracks were collected in the shallow field. A total of forty data collection tracks were run in the two test fields over two days of testing. In each of these tracks, raw sonar and navigation data were recorded for post-processing and analysis. A detailed look at the track lines and measured target positions is provided in Figure 23. In this figure, the individual target positions are called out with red markers.

Operation of the test platform revealed one engineering challenge that must be addressed prior to large-scale survey operations, namely that it is difficult for a human boat operator to maintain a straight track line with limited visual clues, particularly in the presence of even a slight cross-wind or current. A heads-up display was created to show the boat operator their position relative to the installed target positions, and this helped to improve the track positioning. Further work will be conducted this summer to refine that operator

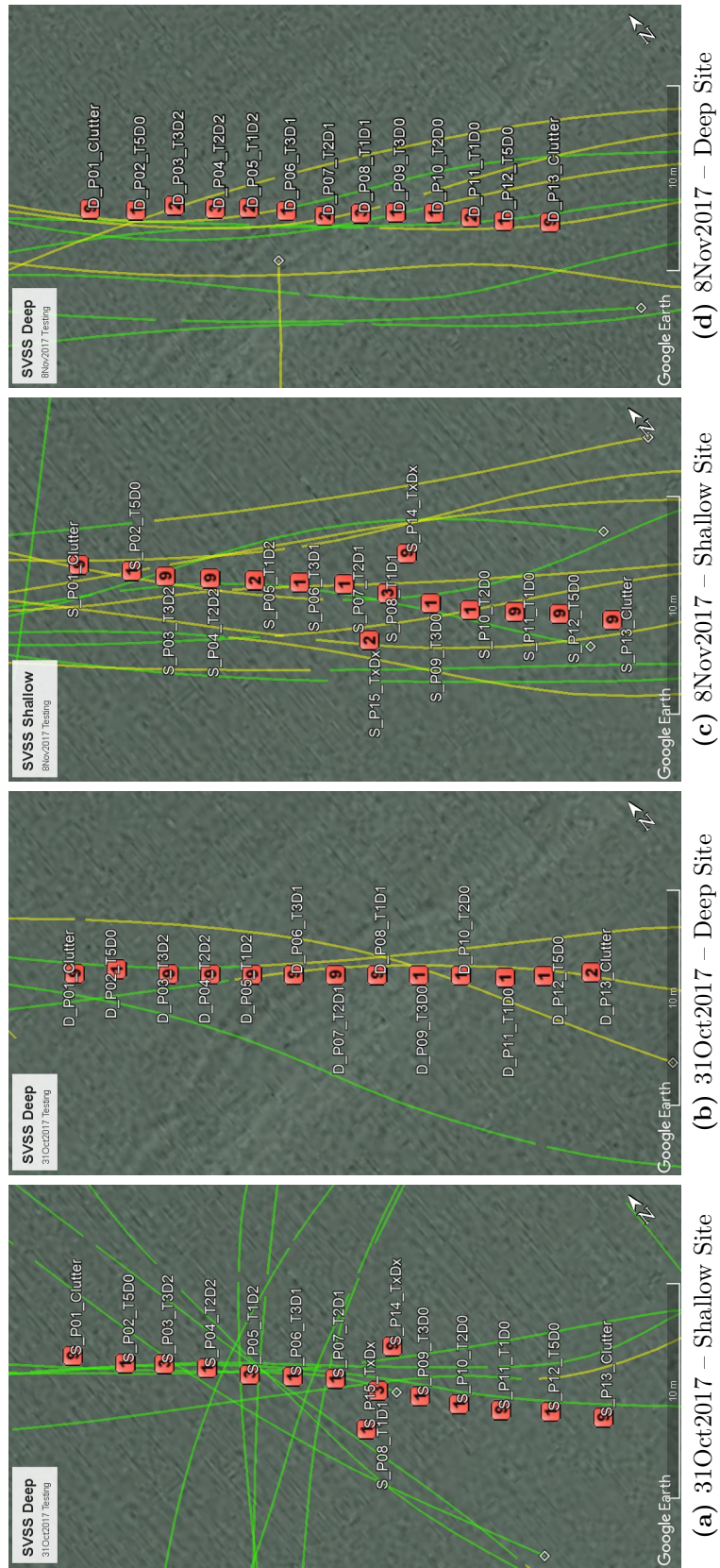


Figure 23: The SVSS sensor paths are shown in detail for each test site and both of the data collection days.

display. Regardless, reliable un-aided track spacing will be difficult during operation in high-wind or strong-current conditions.

3.2.1 High Frequency Sidescan Results

To provide the operator with real-time feedback of the boat position relative to the target track, as well as to avoid obstacles since the SVSS operates in very shallow water, the SVSS was equipped with a Humminbird Helix 10 imaging sonar system. This system acquires sidescan sonar imagery at three optional frequencies: 455 kHz, 800 kHz, and 1.2 MHz. The 1.2 MHz band provides the highest resolution at the expense of imaging range, approximately 10 m, because of increased absorption at this frequency. After integration, ARL/PSU determined this sensor could record the sidescan imagery in a format where it may be post-processed, and was collected during certain testing periods. An example of this imagery is shown in Figure 24. In this figure, a surface target is present on the port side of the test platform. We expect to further explore this data product to assess its utility for the detection of surficial ordnance.

3.2.2 Sub-bottom Imaging Results

The ASASIN beamformer was utilized to post-process SVSS data, creating imagery with voxels (i.e. 3-dimensional pixels) that are 2 cm along each dimension. A three-dimensional matrix of voxels is referred to as a “data cube”. Figure 25a provides a schematic showing a single voxel in red and the three principal axes of the data cube. For the SVSS data presented here, the image output size is 2 m cross-track, 15 m along-track, and 2 m depth. Using a 2 cm resolution, the output imagery is a 100x750x100 data cube. Because individual tracks are all greater than 15 m along-track, each track is beamformed into a series of images of this length. This along-track length is a user-selected parameter and may be modified depending on the test conditions.

Two-dimensional visualizations of three-dimensional imagery are generated either as “slices” through, or “projections” of, the original data cube. A planar slice through the volume creates a single two-dimensional plane. These slices may be taken along any of the three principal axes; an example is shown in Figure 25b. Another representation that is commonly used is the maximum intensity projection (MIP). A MIP is formed by collapsing the imagery along one of its principal axes and taking the highest intensity voxel [15]; a schematic example of this projection is shown in Figure 25c.

Figure 26 shows each sliced data representations for the first image in the track 2017 1031 170702. Each slice individually normalized by its peak value. In Figure 26b, a short cylindrical target, S_P07_T2D1, and a long cylindrical target, S_P06_T3D1, are seen

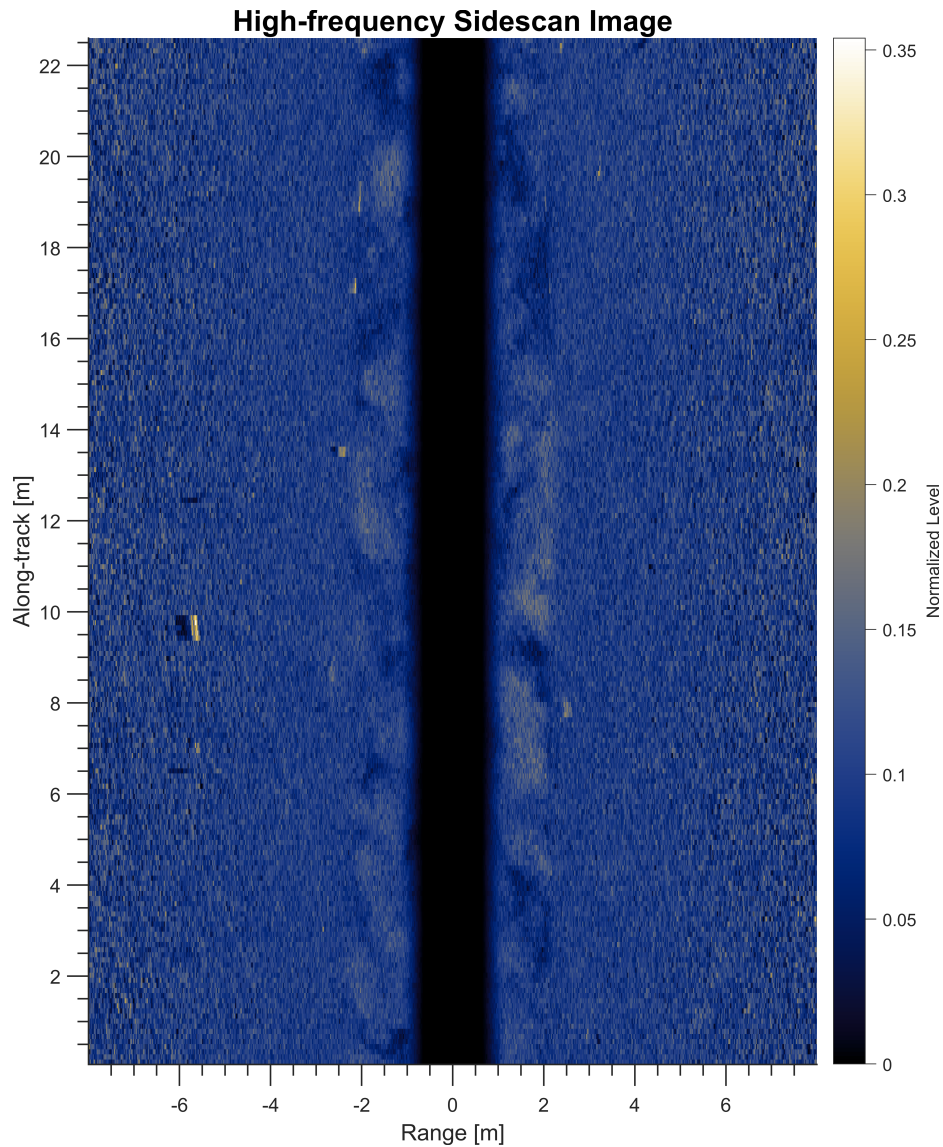


Figure 24: A Humminbird Helix 10 sidescan sonar was used to collect high-frequency imagery of the seafloor during certain test periods. The image shown here was collected using the 1.2 MHz band. This data has the potential to inform operators about surficial targets and clutter, as well as to improve situational awareness when operating in very shallow water.

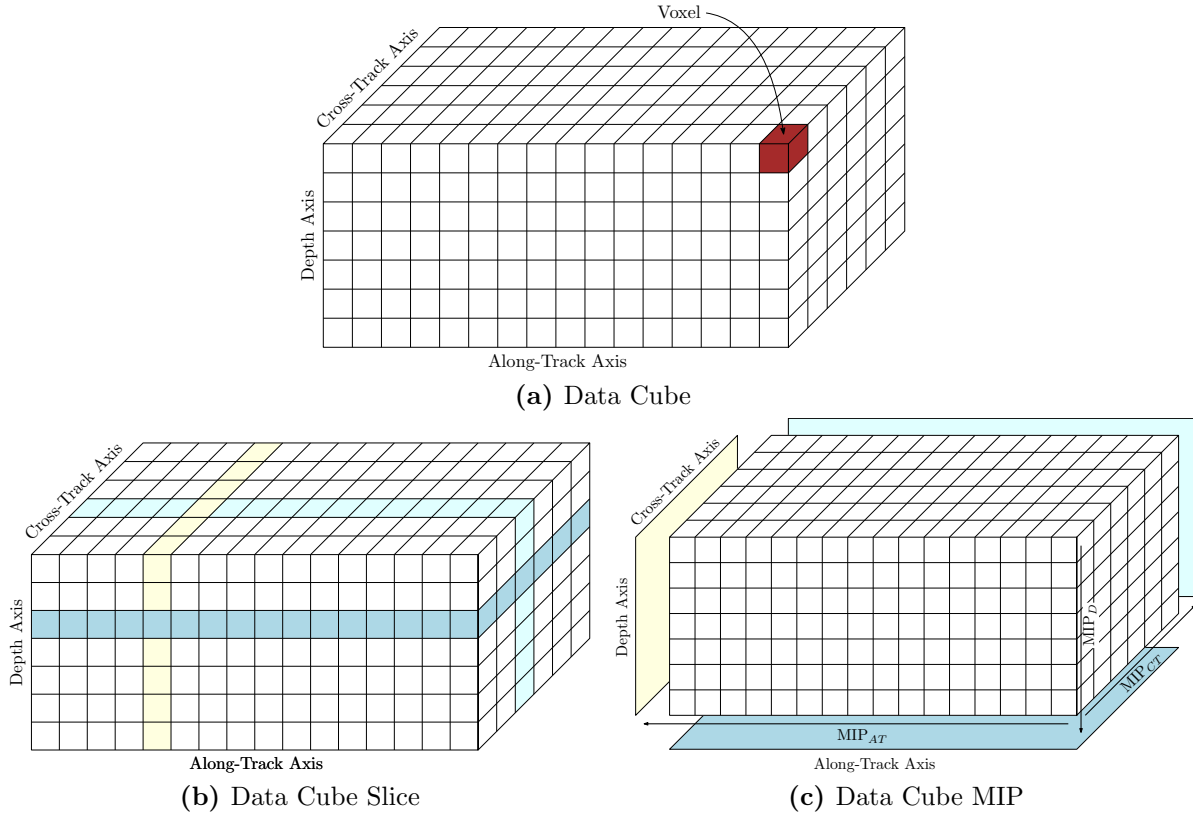


Figure 25: A pair of two-dimensional data representations is used to visualize the imagery. Figure (b) shows slices through the three-dimensional data which are taken at discrete positions along one of the three principal axes. Figure (c) shows maximum intensity projections (MIPs) along the principal axes. The along-track slice and MIP are shown in yellow. The cross-track slice and MIP are shown in light blue. The depth slice and MIP are shown in dark blue.

at 3 m and 5 m along-track, respectively¹. The silt/water boundary is barely visible in the cross-track slice, Figure 26a, at a depth just above the large cylindrical target. The silt/clay boundary is seen beneath the large cylinder and it produces a relatively strong return.

The two cylindrical targets seen in Figure 26 are shown in greater detail in Figure 27. In the left column of this figure, the targets are shown using a logarithmic color scale. The right column shows target cross sections drawn in the along-track, cross-track, and depth directions through the peak target response. These cross sections are all aligned to have their peak value at zero displacement. Data were collected such that the long axis of each cylinder is approximately aligned with sensor's track. Therefore, the cylinder's

¹The target naming convention is defined in Section 2.4.2. Briefly, {S,D} defines the test field depth, {P##} is the position within the test field, {T#} is the target identifier, and {D#} is the notional burial depth.

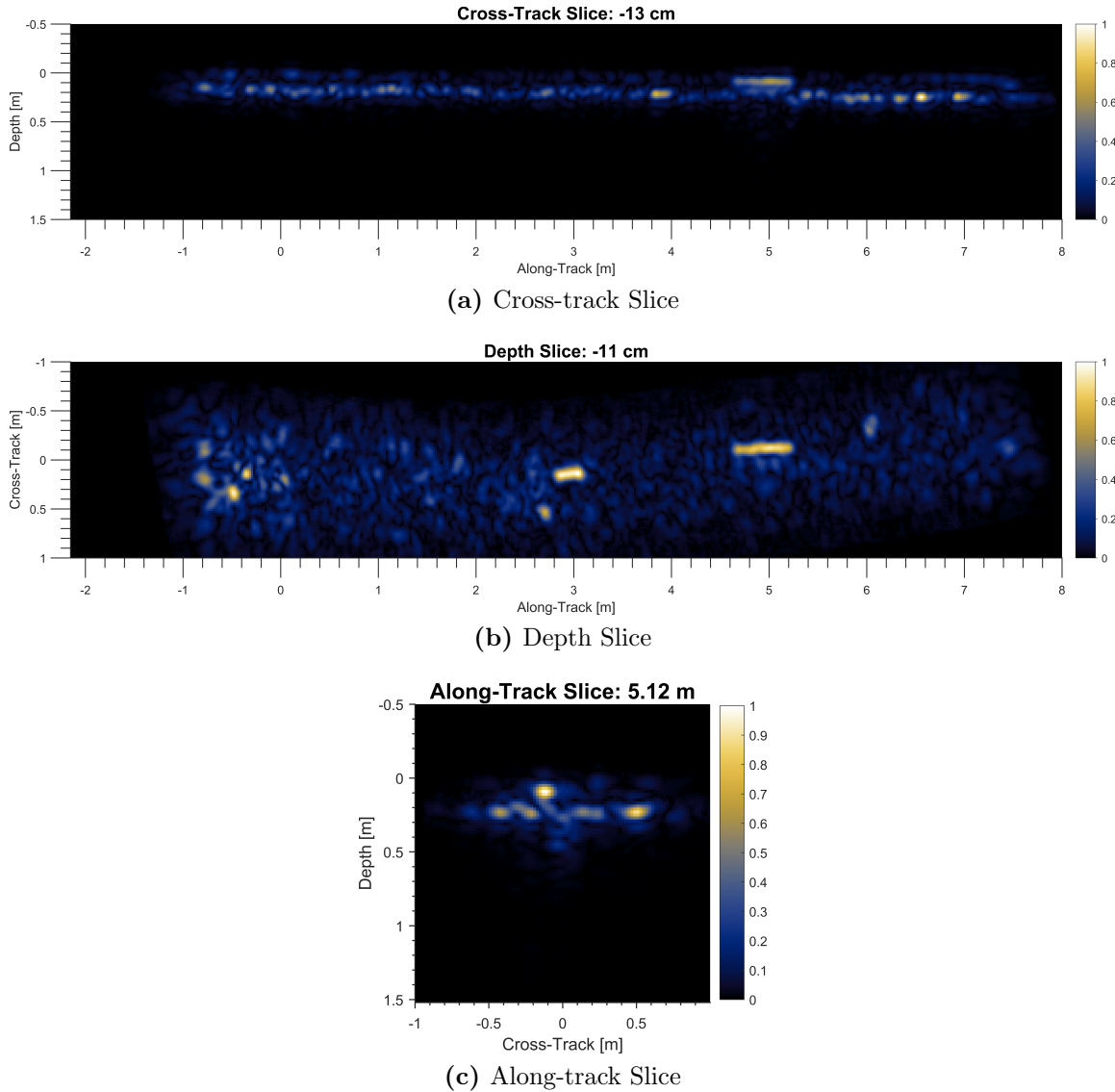


Figure 26: Three slices are shown for the first image of track 2017 1031 170702. The slices pass through the large cylindrical target (S_P06_T3D1). A small cylinder (S_P07_T2D1) is also seen in the depth slice. Each slice is shown on a linear scale with the peak set to the slice's maximum voxel value.

length is given by the width of the along-track cross section and the cylinder's diameter is given by the width of the cross-track cross section. The true target dimensions are given in Table 2. Analysis of the cylinder cross-sections shows that the SVSS is capable of creating accurate target dimension estimates. A complete set of cylindrical target images as well as target cross sections are provided in Appendix B.

The detection of targets in the volumetric imagery is complicated by the reflectivity of the silt/clay boundary. Some points along the boundary in Figure 26b actually exceed the scattering level observed for the cylindrical target. The linear scale used in Figure 26

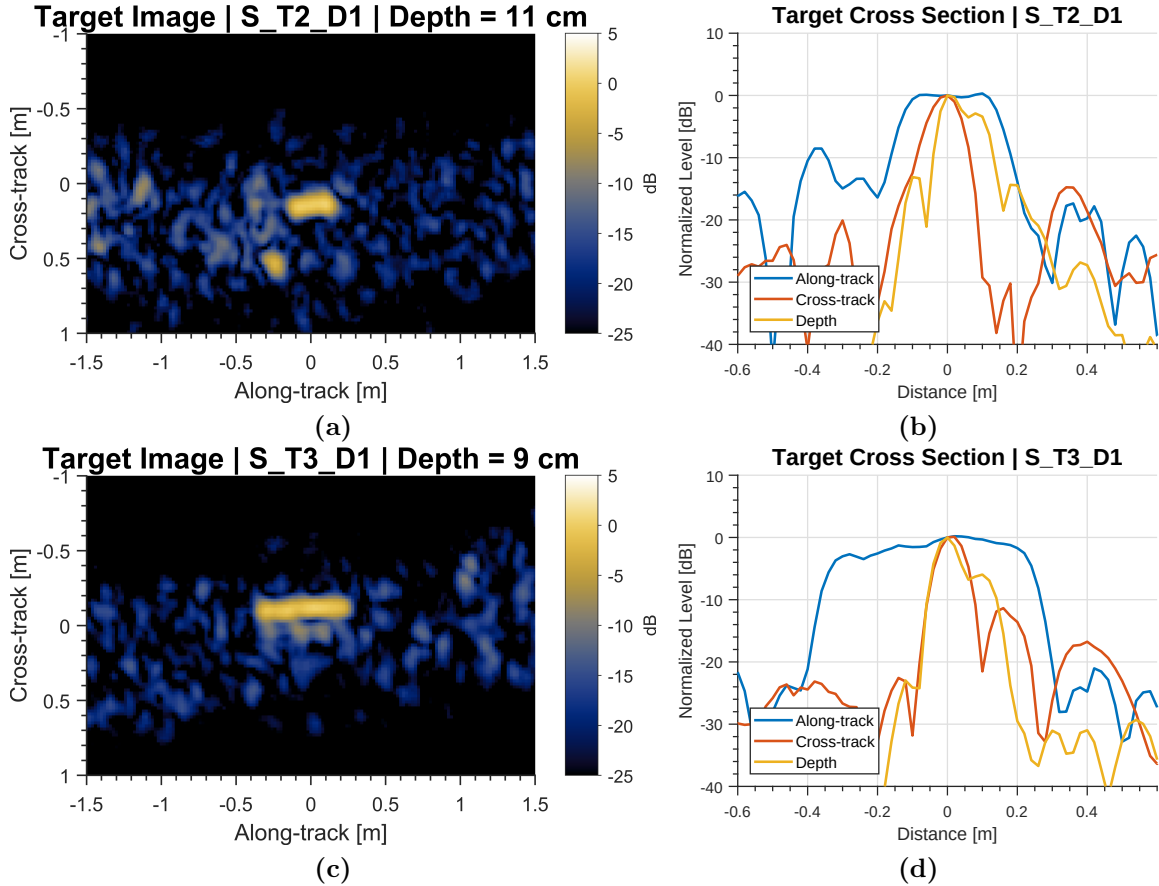


Figure 27: Imagery is shown for the depth slice through the targets S_P07_T2D1 (a) and S_P06_T3D1 in (c). For each target, cross sections along the three principal data axes are shown in (b) and (d).

limits visual interpretation of returns from the deeper sediment. The strong reflection from the silt/clay boundary, combined with the spreading loss and sediment attenuation, reduces the strength of the sub-bottom return to the point where it is not visible with this image.

The wide dynamic range of scattering present in the SVSS imagery requires some type of background estimation to make the imagery interpretable. This type of background estimation is commonly used within the sonar machine learning community [16,17]. For data presented here, the background was estimated using a median filter with a three-dimensional kernel whose dimensions are 0.2m cross-track by 1.2m along-track by 0.1m depth. After the raw data are normalized by the background estimate, they are further processed with a dynamic range compression (DRC) algorithm. This algorithm applies a combination of logarithmic mapping and nonlinear intensity mapping operators to further compress the most extreme sample values.

The data used to form the slices in Figure 26 have been processed by the background estimation and DRC algorithms. The slices from the scaled data are shown in Figure 28.

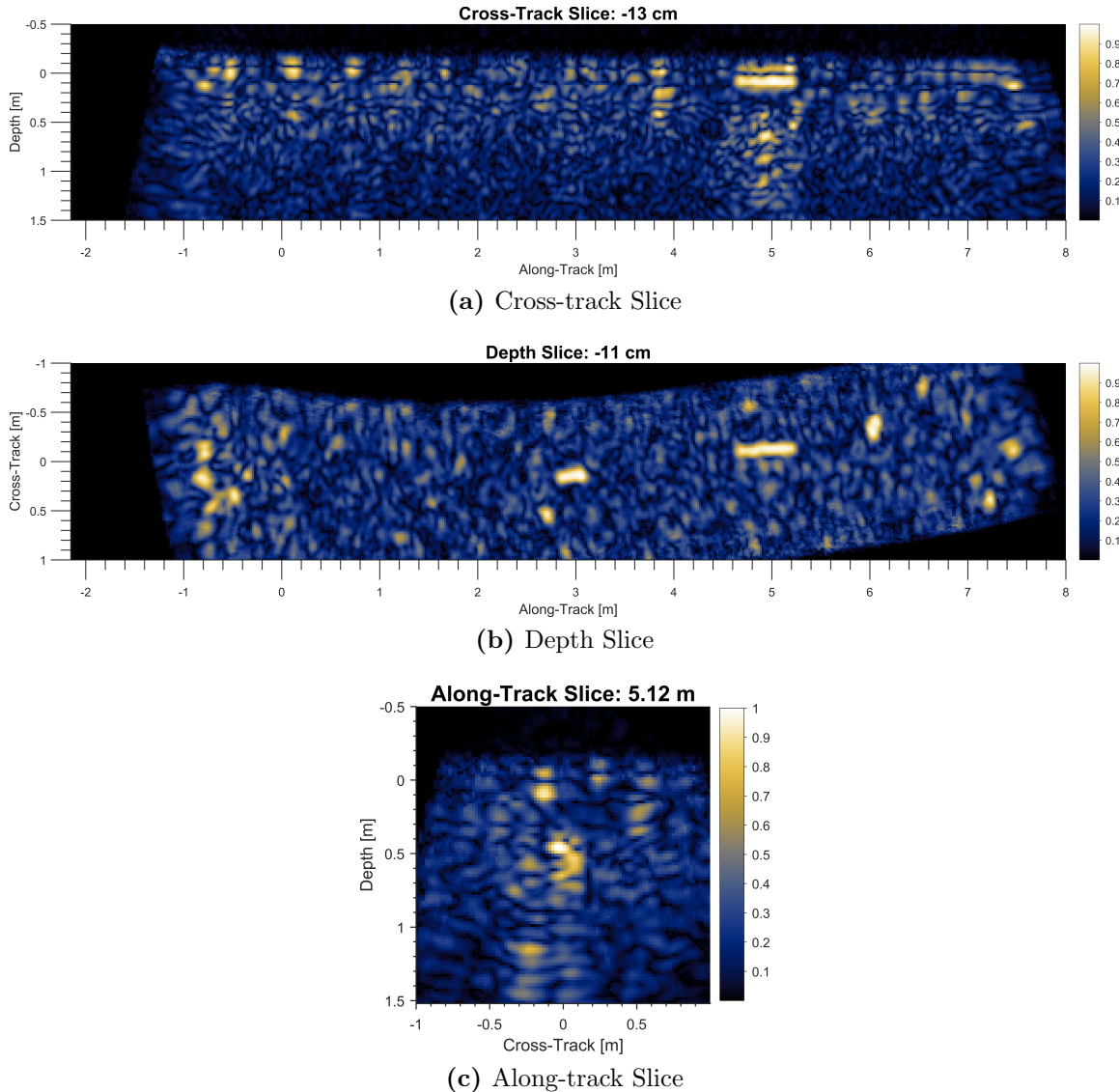


Figure 28: Background estimation and dynamic range compression has been applied to the data shown in Figure 26. This nonlinear mapping aids interpretation by reducing the overall dynamic range of the imagery.

This process has increased the intensity of the sub-bottom returns so that buried objects may be more clearly recognized. However, normalization of the level versus depth has some drawbacks for image interpretability. The transition from silt to clay is no longer observable. Additionally, the normalization of the strong silt/clay return produced artificial horizontal banding in the upper 10-15 cm of the lake bed. The background estimation process shown here represents a first attempt at adaptive normalization. These background estimation algorithms must be further researched for sub-bottom imaging systems. This is especially true for data that will be reviewed by human operators.

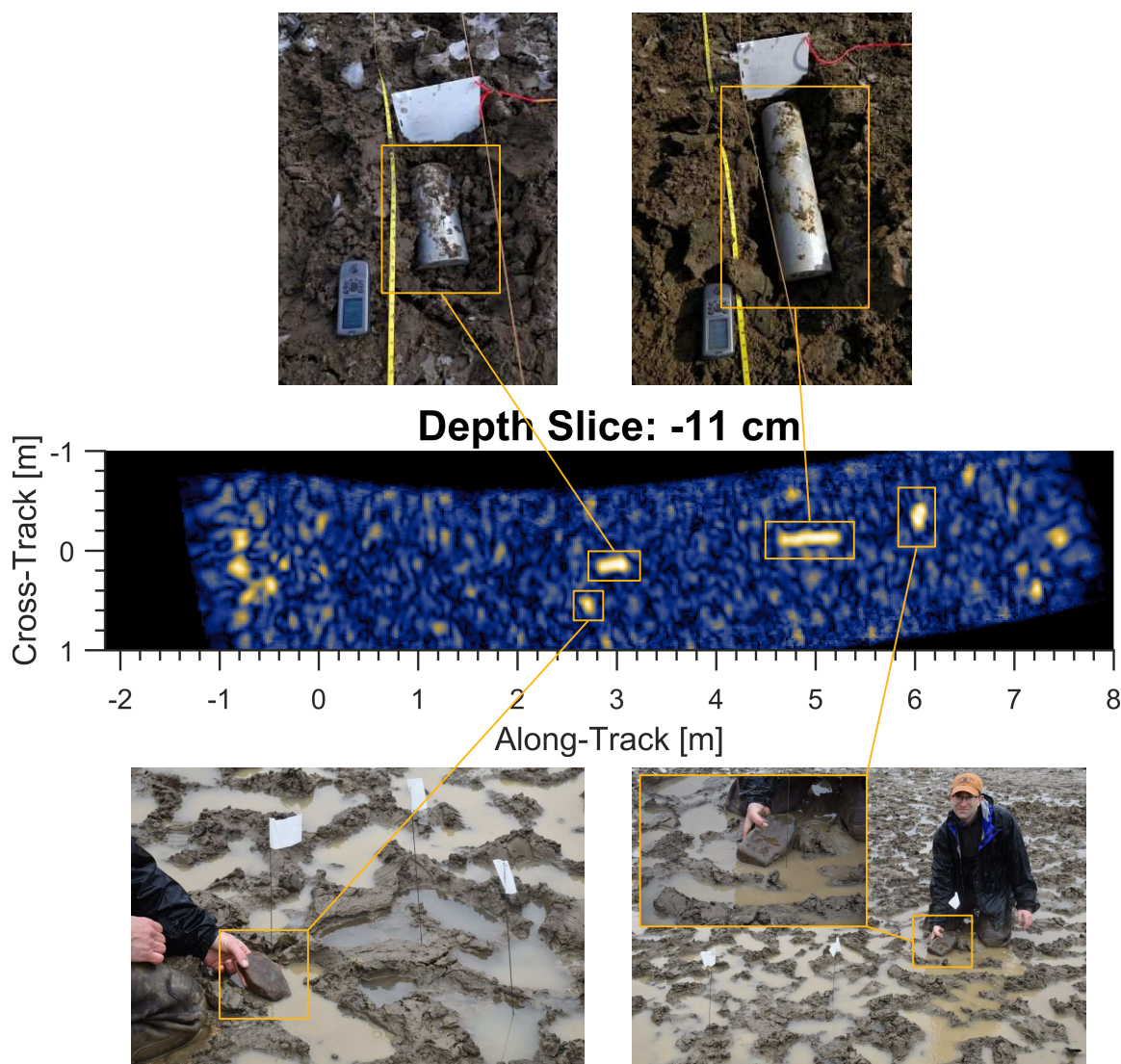


Figure 29: Two clutter targets were identified in the depth slice shown in the middle figure. During the installation of a second target field in March 2018, the clutter objects were determined to be the pair of rocks shown in the bottom photographs.

The depth slice shown in Figure 28 clearly shows the pair of cylindrical targets at 3 m and 5 m along-track. There are also several additional returns that are nearly the same scattered level in the imagery. In particular, there is a bright return at 2.7 m along track and 0.5 m cross-track, and another bright return at 6 m along track and -0.3 m cross-track. The cylindrical targets and clutter object positions are called out in Figure 29. During the installation of the second test field in March of 2018, the ends of two cylindrical targets were located and marked with flags. Using the sonar imagery, the locations of the two clutter targets relative to the two cylindrical targets were calculated. Upon placing flags at both calculated positions, the two flat rocks shown in the lower frames of Figure 29 were found and recovered. Each rock was found with a flat face oriented upward, which is the

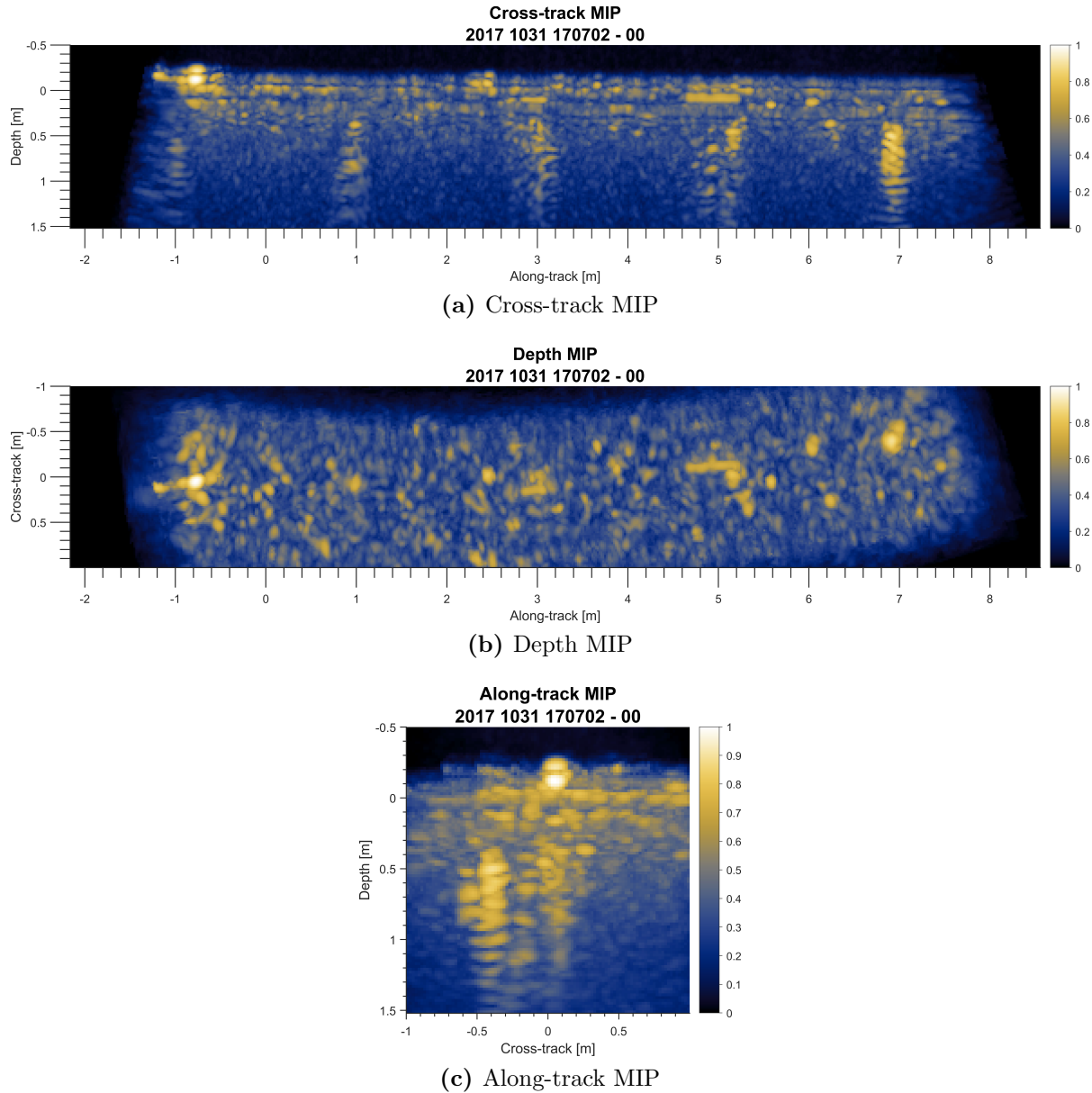


Figure 30: Maximum intensity projections are shown for a selected image.

likely cause for the relatively strong returns. This post-acoustic-survey localization and recovery of modest sized buried objects serves as a demonstration of the SVSS potential for target detection and localization.

The survey data has also been processed to form MIPs along the three principal axes. These are shown in Figure 30 after the data were preprocessed with the background normalization and DRC algorithms described above. Targets were placed every 2 m in the test field, and evidence of target return are seen at -1 m, 1 m, 3 m, 5 m, and 7 m along-

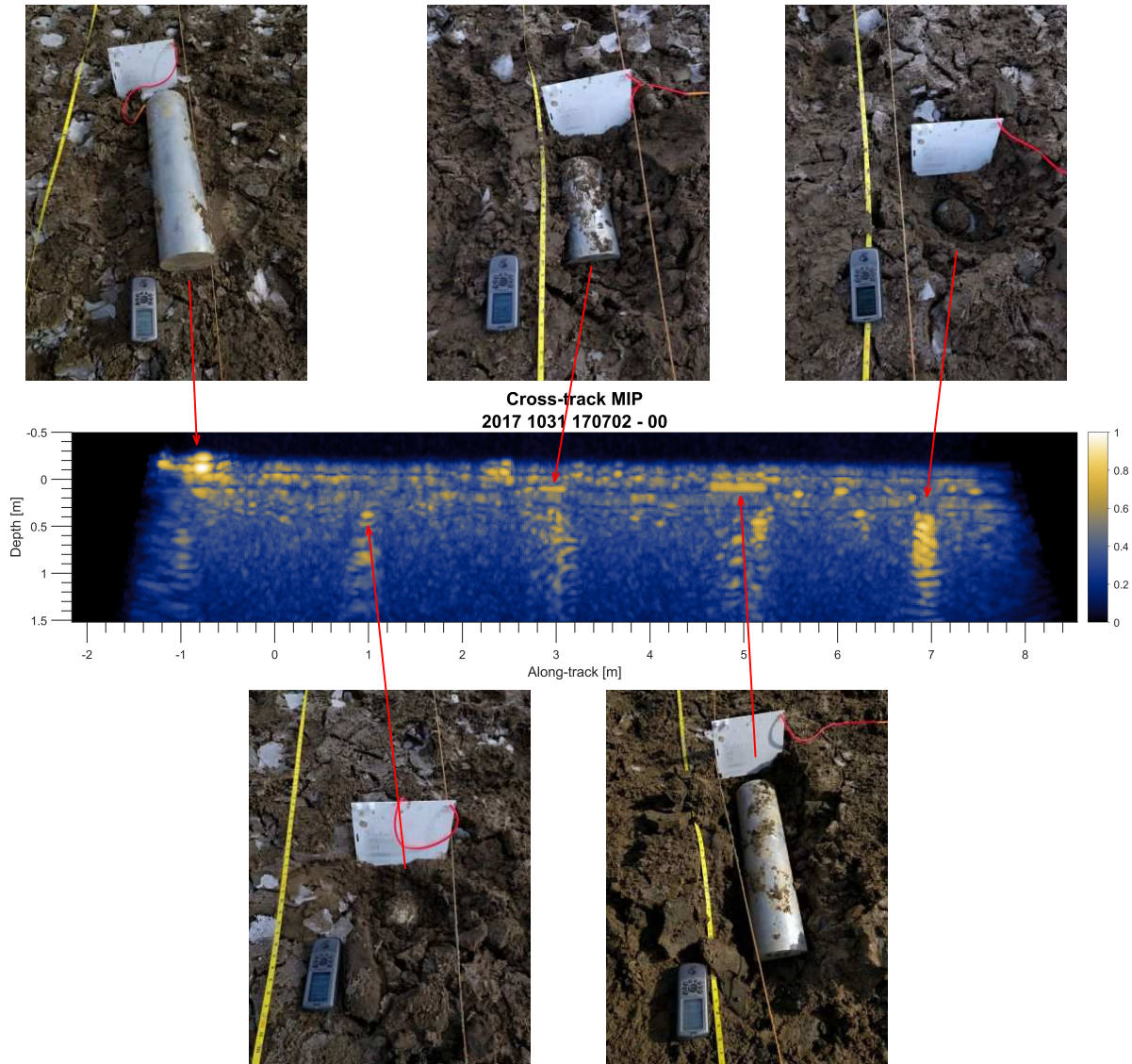


Figure 31: Five targets, S_P09_T3D0, S_P08_T1D1, S_P07_T2D1, S_P06_T3D1, and S_P05_T1D2, are shown in a cross-track MIP along with their installation photos.

track. These positions correspond to the targets S_P09_T3D0, S_P08_T1D1, S_P07_T2D1, S_P06_T3D1, and S_P05_T1D2, respectively. The target installation photos and the cross-track MIP are shown in Figure 31. The large surface cylindrical target, S_P09_T3D0, is distorted because it is truncated by the boundary of this image. Each of these targets shows a decaying return versus depth that extends far beyond the actual target dimension. It is hypothesized that these returns are due to elastic scattering phenomena. It is interesting that for the shot puts the level of the scattered elastic field appears to exceed that of the specular scattering. This result is a combination of two factors. The first is that, in this location, the shot puts are placed near the silt/clay boundary which has a comparably strong acoustic reflection, effectively masking the specular response of

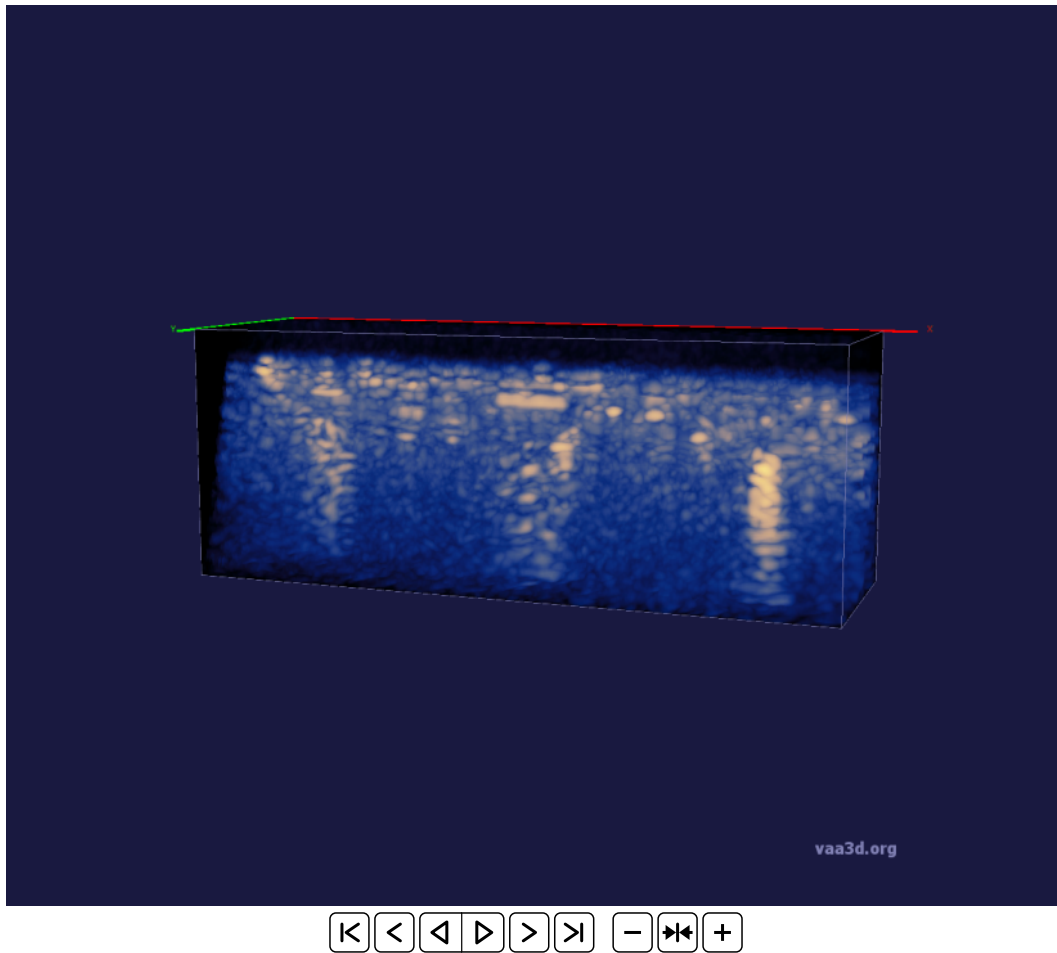


Figure 32: Three targets, S_P07_T2D1, S_P06_T3D1, and S_P05_T1D2, are shown in a three-dimensional animation. The animation is only supported when the document is viewed using an Adobe Acrobat reader.

the shot put. The second factor is the result of the background normalization effectively enhancing what is suspected to be the elastic response of the shot put. The result in this scenario is that the target return itself may not be directly observed in the imagery, yet the elastic response is clearly evident.

A subset of the imagery investigated in this section has been processed using a three-dimensional data viewer called VAA3D [18]. This viewer permits manipulation of the full data cube without the need for dimensionality reduction through slicing or projections. In Figure 32, a subset of a data cube is shown in an animation rotating about the depth axis. Targets S_P07_T2D1, S_P06_T3D1, and S_P05_T1D2 are seen in this figure.

In Table 5, target detection and localization results are summarized for the combined 31Oct2017 and 8Nov2017 tests. The install depth reported is from measurements during target installation in 2017, the survey depth reported is from measurements during the

resurvey of the test field in 2018, and the imaged depth reported is from measurements of the sonar imagery. Target latitude and longitude positions are provided along with the track and image number where the target was detected. Finally, a qualitative “detection quality” score is provided in the final column. The detection quality is defined as:

- 1 - Target is clearly visible and recognizable in imagery.
- 2 - Target is visible in imagery, but recognition is difficult.
- 3 - Target is visible in imagery, but only recognized due to layout geometry. This case includes those where the shot put was detected from visible elastic returns.
- 9 - Target not observed in imagery.

Table 5: Installed target positions and detection results.

Target Identifier	2017 Install Depth [cm]	2018 Survey Depth [cm]	Imaged Depth [cm]	Latitude [deg]	Longitude [deg]	Track Detected	Detection Quality
S_P01_Clutter	7	- ^a	- ^b	41.001479006315	-77.678954026229	-	9
S_P02_T5D0	0	0	0	41.001462638440	-77.678934199829	2017 1108 180731 4	1
S_P03_T3D2	11	10	15	41.001452046376	-77.678917694499	2017 1031 170702 1	2
S_P04_T2D2	9	9	15	41.001439391794	-77.678900869985	2017 1031 170702 1	1
S_P05_T1D2	19	9	- ^c	41.001425954575	-77.678884941550	2017 1031 170702 0	3
S_P06_T3D1	3	3	9	41.001413916724	-77.678867129042	2017 1031 170702 0	1
S_P07_T2D1	5	6	11	41.001401893779	-77.678849671622	2017 1031 170702 0	1
S_P08_T1D1	7	7	- ^c	41.001386695481	-77.678835666258	2017 1031 170702 0	3
S_P09_T3D0	0	0	0	41.001373724538	-77.678819618933	2017 1108 180731 2	1
S_P10_T2D0	0	0	0	41.001360825996	-77.678805703267	2017 1108 180528 1	1
S_P11_T1D0	0	0	- ^b	41.001347731697	-77.678789842148	-	9
S_P12_T5D0	0	0	0	41.001334057438	-77.678769118083	2017 1031 170347 0	1
S_P13_Clutter	7	- ^a	- ^b	41.001318179956	-77.678748657209	-	9
S_P14_TxDx	31	- ^a	- ^b	41.001397220000	-77.678813888889	-	9
S_P15_TxDx	33	- ^a	0 ^d	41.00137273873	-77.678854157438	2017 1031 171953 6	1
D_P01_Clutter	0	- ^a	- ^b	41.005348755759	-77.674658249091	-	9
D_P02_T5D0	0	0	0	41.005339075670	-77.674638741338	2017 1108 183326 3	1
D_P03_T3D2	17	14	15	41.005323668459	-77.674618184922	2017 1108 183612 5	2
D_P04_T2D2	17	15	- ^b	41.005312531350	-77.674600408209	2017 1108 183326 3	3
D_P05_T1D2	19	16	15	41.005301394240	-77.674582631496	2017 1108 183326 3	2
D_P06_T3D1	- ^e	6	11	41.005290257131	-77.674564854782	2017 1108 183326 3	1
D_P07_T2D1	5	6	13	41.005279120022	-77.674547078069	2017 1108 183942 2	3
D_P08_T1D1	11	10	- ^c	41.005267982912	-77.674529301356	2017 1108 183942 2	3
D_P09_T3D0	0	0	0	41.005256845803	-77.674511524643	2017 1108 183058 3	1
D_P10_T2D0	0	0	0	41.005245619082	-77.674493540841	2017 1108 183058 3	1
D_P11_T1D0	0	0	0	41.005233189519	-77.674475402658	2017 1031 174352 1	1
D_P12_T5D0	0	0	0	41.005223434475	-77.674458194503	2017 1031 174352 1	1
D_P13_Clutter	- ^e	- ^a	15	41.005211949761	-77.674436588706	2017 1031 174352 1	2

^aDepth not recorded during survey.^bTarget not observed in imagery.^cShot put detected from elastic response. No valid depth estimate.^dSurface ladder detected. Buried shot put not detected.^eDepth not recorded during installation.

3.3 Target Localization Results

The test platform is equipped with an IxBlue PHINS inertial navigation system that is externally aided with GPS inputs, and the PHINS serves as the primary sensor responsible for generation of navigation output. Two different GPS differential correction sources were used during the test period. Testing leading up to and including 31Oct2017 utilized a satellite-based augmentation service (SBAS) configuration. SBAS has a quoted baseline accuracy of 50 cm. A real-time kinematic (RTK) base station was utilized for imagery collected on 8Nov2017. In using this type of differential correction source, the RTK base station generates local GPS error estimates. These estimates are then transmitted to the SVSS's GPS receiver using a radio, so that it may account for the error in the generation of its position fix. This type of configuration has the potential to achieve 1 cm absolute accuracy.

The positions have been calculated for the targets that were detected during both collections, and their offsets are provided in Table 6. The root mean square error (RMSE) was found to be 25 cm. The target localization error between the two collections with the two different types of differential correction was within the error bounds of the SBAS accuracy.

Table 6: Relative re-localization accuracy was quantified between the observed target positions on 31Oct2017 and 8Nov2017.

Collection Comparison	Mean Error [cm]	Std. Dev. [cm]	RMSE [cm]
31Oct2017 (SBAS) – 8Nov2017 (RTK)	22.6	11.4	25.1

Prior to the 2018 testing season, ARL/PSU plans to have a survey conducted to identify a suitable permanent site for an RTK base station to be installed near the test site. Once this base station is surveyed and installed, it will be possible to provide an accurate assessment of the absolute target positioning accuracy of the SVSS sensor.

4 Conclusions to Date

4.1 Go/No-Go Decision Criteria Conclusions

A prototype SVSS sensor was tested and shown to provide a three-dimensional imaging capability for buried UXO. This demonstration required substantial work in several areas. First, a new acoustic projector was developed and integrated to an existing test platform. Second, a pair of test fields were installed with a range of targets and target burial depths. Finally, the existing signal processing algorithms were advanced to improve the quality of the imagery generated by the system. The result of ARL's efforts across these areas is the successful demonstration of a buried UXO imaging sonar system designed for operation in very shallow water.

This technical report is associated with a Go/No-Go decision point. The key questions and topics ARL/PSU was asked to address with respect to this decision point are:

- demonstration of methods for mitigation of multipath reverberation,
- characterization of target detection across a range of water and sediment burial depths,
- characterization of target localization accuracy,
- mitigation of the effects of platform motion on system performance, and
- mitigation of the effects of variability in sediment properties on performance.

The SVSS sensor relies on passive isolation in the design of the source and receive arrays to provide rejection of the first-order multipath. The projectors developed in this phase of the program have in excess of 30 dB passive isolation. This design resulted in imagery that was not limited by first-order multipath interference.

A pair of target fields were installed at the Foster Joseph Sayers Reservoir in March of 2017. Three different "science" objects as well as a few types of clutter targets were installed in the test area, across a range of water and sediment burial depths. The SVSS was able to detect 11 of the 12 cylindrical targets deployed. The shot put targets, whose size is near the theoretical resolution of the sonar and which have a significantly lower target strength, were more difficult to detect. However, the presence of several shot puts was visible due to strong elastic scattering. These results point the way towards potential target detection and classification. New targets were installed in March 2018 to further characterize the performance of the SVSS against realistic ordnance and discrimination against clutter during future testing.

Two different GPS differential correction sources were used in the survey testing. Satellite-based augmentation service (SBAS), with a quoted baseline accuracy of 50 cm, was utilized for imagery collected on 31Oct2017. A real-time kinematic (RTK) base station, which can potentially achieve 1 cm accuracy, was utilized for imagery collected on 8Nov2017.

Target localization error between the two passes with the two different types of differential correction was within the error bounds of the SBAS accuracy. Future testing will exclusively utilize RTK-aided navigation. As a demonstration of target localization and reacquire, two clutter objects were identified in an image collected on 31Oct2017. During the March 2018 target installation, these two clutter items (rocks) were recovered in the positions derived from the sonar imagery.

As part of the Phase 1 technical report, ARL/PSU hypothesized that the adverse effect of platform motion would be mitigated by the high-grade inertial navigation system installed on the test platform. The images generated in this phase do not show any of the typical defocusing effects associated with uncompensated motion in SAS image formation [19]. In the event these errors do become an issue in future testing, the team has extensive experience in the development of synthetic aperture sonar signal processing and motion estimation algorithms [20–22].

The test area used for the SVSS demonstration has a layered lake bed with a thin silt layer overlaying a clay basement in the shallow field and a more homogenous silty clay sediment in the deep site. Buried targets were detected in both test sites; however, the quality of the imagery in the deep site was lower than that observed in the shallow site. The ARL/PSU team made numerous attempts to collect a core during the test period. Unfortunately, a combination of the sediment properties, water depth, and test platform size limited the extraction of meaningful sediment samples. To address this shortcoming, ARL/PSU has collected numerous cores during the drawdown period, which will be re-wet to mimic the lake refilling, and characterized by sediment experts at the Naval Research Laboratory - Stennis. We look forward to providing a more detailed analysis of the impact of sediment variability on sensor performance.

4.2 Future Work Based And Challenges

During Phase 2 development, testing, and analysis, there were several topics identified which could improve understanding of the environment and performance of SVSS. In this section we will outline several of these areas, any of which may be included in follow on work. These include the following topics, in no particular order.

4.2.1 Enhanced Target Detection

A heuristic image normalization method was developed to improve target visualization. This method, presented previously in this report, works well to control the wide dynamic range of data collected with the SVSS. However, one aspect which we feel can be significantly improved is when a weaker target return is masked by a stronger water-sediment or sediment layer interface reflection. For several examples, elastic effects were clearly observed as “ringing” although the impulsive specular target return was obscured by an interface reflection. It should be possible to enhance target detection by exploiting these

elastic effects. One promising approach, based on Prony spectral analysis, was presented by Cook at the recent SAGEEP 2018 meeting [23]. Collaborators at GTRI and within ARL/PSU are investigating application of Prony analysis which may be leveraged for this program. We feel this technique lends itself nicely to the current SVSS data products and should be relatively straightforward to implement, and if successful may improve target detection. This technique would also leverage techniques that other SERDP researchers are investigating since it has close ties to Acoustic Color. There may be other Acoustic Color or image processing techniques which could be exploited.

4.2.2 Improved Sediment Characterization

During Phase 2 several sediment cores were obtained to characterize the sediment geoaoustic properties, namely sound speed and attenuation. Obtaining these cores from the sonar platform proved to be particularly challenging owing to shallow water depths, which precluded gravity coring, and sediment stiffness, which minimized the effectiveness of vibra-coring. Additionally, preliminary analysis of the SVSS data indicate sediment layering and interface roughness variability are beyond what can be quantified by isolated sediment cores. Since this environmental variability may significantly impact the performance, we propose *in situ* sediment characterization will be necessary for a fielded version of the SVSS. Sediment sound speed may be estimated from the SAS beamforming process itself since this is an essential parameter for sharp image formation. Sediment attenuation maybe estimated from the collected data since individual elements of the SVSS are calibrated prior to field trials. Additionally colleagues at partner institutions have experience developing acoustic (ARL:UT) and (electrical) impedance-based (APL-UW) sediment characterization techniques. Any of these topics could be explored in more depth to improve performance characterization.

4.2.3 Wideband Transmitter Study

With the departure of ITC from the commercial sonar transducer market early 2017, ARL/PSU was in a position to quickly fabricate transmitters to be able to test during the 2017 season. Although results with the current transmitters are promising, there is always the potential for improvement. ARL/PSU has experience developing wide bandwidth acoustic transmitters which can be leveraged. Additionally a study could be conducted, in combination with advances identified in the previous improved target detection and improved sediment characterization sections above, to identify what frequencies and bandwidths might be more optimal for a particular target in a particular environment. For example, it may be possible to elucidate what frequency causes a strong elastic response to exploit Prony analysis when a particular target is sitting on a strongly reflecting sediment interface.

4.2.4 Ensuring Area Coverage / Multi-pass Fusion of Data

Although navigational accuracy of SVSS data is high, Phase 2 did not address obtaining 100% area coverage. It was noted positioning the platform in a dynamic environment was challenging owing to the relatively narrow footprint of SVSS. Similarly, although tools are in place to present multiple data passes in a geo-spatial format (i.e. GeoTIFF) for display in post-processing software (e.g. Google Earth), blending of multiple SVSS images has not yet been addressed. These two topic areas should be addressed for any fielded version of the SVSS. Such a solution could take the form of a blended Heads-Up Display for the platform pilot and/or navigation autonomy.

4.3 Concluding Remarks

In conclusion, the SVSS sensor has been tested across a pair of water depths and variety of target burial depths. The data analysis presented in this report shows that the system design mitigates the impact of multipath interference. Additionally, the sensor is capable of buried target detection and accurate localization. It is our opinion that the basic SVSS design is validated by this prototype demonstration and Phase 3 development and testing is warranted.

A Sonar Hardware Calibration and Characterization

The sonar hardware used on the Sound Hunter test platform was characterized at the Foster Joseph Sayers Reservoir test site and calibrated at the ARL/PSU Anechoic Test Facility (ATF). Noise characterization conducted at the test site is presented in the following section. The ATF test facility has the capability to test sonar hardware at frequencies above 5 kHz for pulse lengths up to 2 ms. The calibration of the projectors, whose design was described in Section 2.2.1, is provided in Section A.2. The hydrophone calibration is provided in Section A.3.

A.1 Sensor Noise Floor Characterization

Early field testing was focused on verifying the sensor integration, and one key measurement was the characterization of the receiver noise floor. The integration of new hydrophone modules, transmit amplifiers, and projectors carries the risk of introducing new electronic self-noise mechanisms. In initial integration tests on 13Sep2017, it was discovered that the amplifier grounding scheme had introduced a ground loop responsible for a very significant increase in the noise floor. After the ground loop was identified and rectified, the system's noise floor was measured again on 22Sep2017. The results of this test are shown in Figure 33. This noise floor is roughly 7 dB greater than that observed in deep water (180 m) prior to refitting with SVSS hardware. It is hypothesized that the increase in noise floor is due to scattering of the radiated self noise from the lakebed.

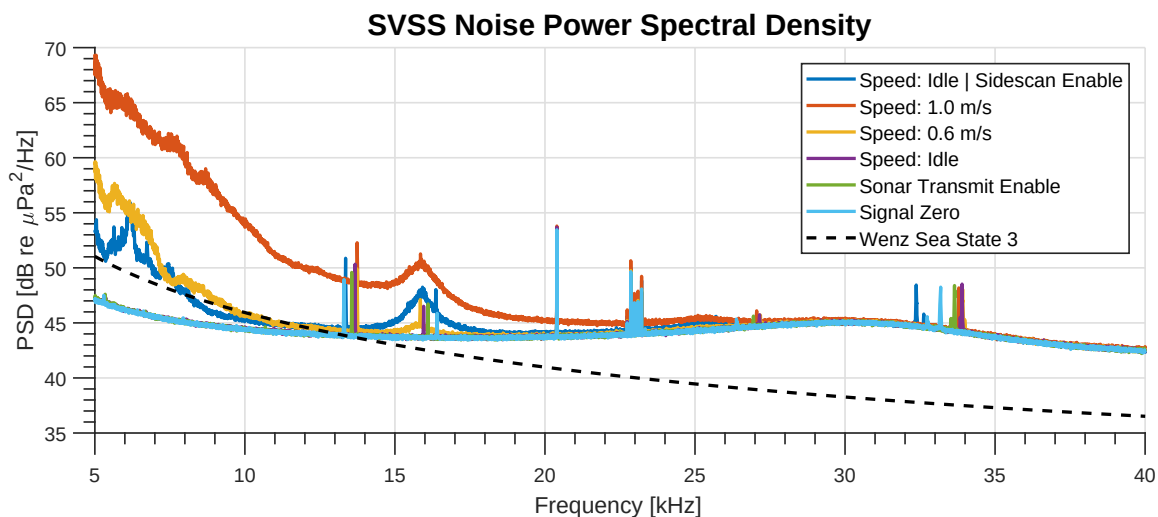


Figure 33: The SVSS system's noise floor was characterized for a number of operating states.

A.2 Projector Calibration

Six projectors were fabricated for the SVSS program, and each projector was characterized in the ATF using the facility's Instruments Incorporated L6 linear amplifier. The Transmit Voltage Response (TVR) was measured using a 1.95 ms, 5-100 kHz, linear frequency modulated waveform. In the band spanning 10-40 kHz, the projector TVRs are well-matched as seen in Figure 34.

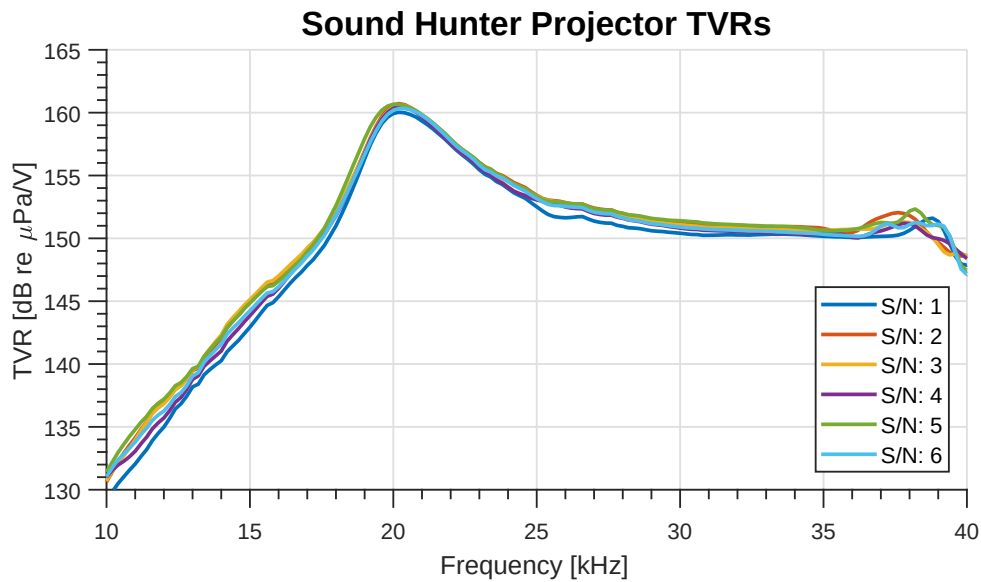


Figure 34: The projector TVRs are well matched over the 10-40 kHz band.

Broadband transmit beampatterns were measured using a 1.95 ms, 10-40 kHz, linear frequency modulated waveform. The full patterns are given in Figure 35, where the axes are transducer aspect angle and frequency. Single frequency beampatterns are provided in Figure 36 over $\pm 45^\circ$ for 20, 27.5, and 35 kHz.

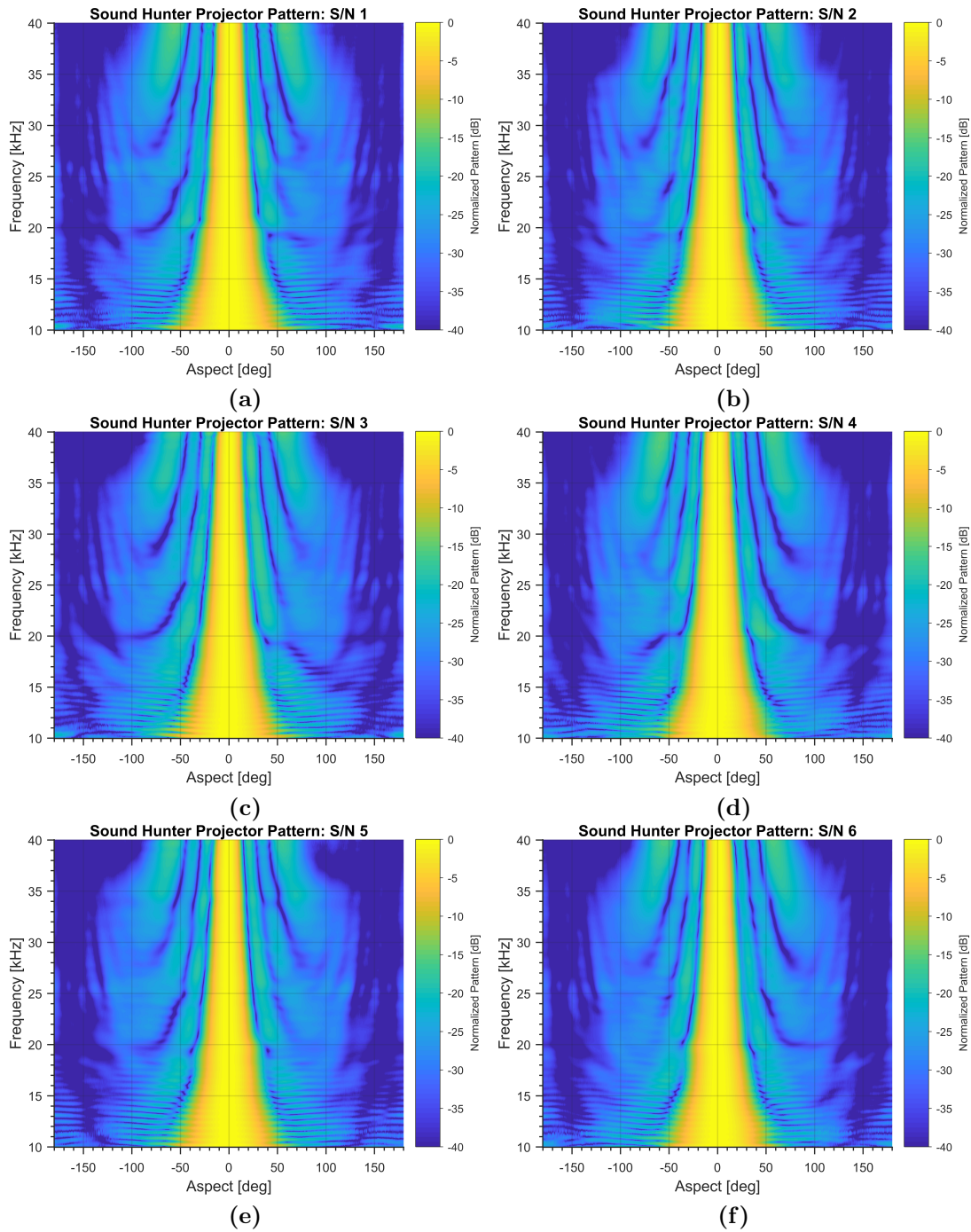


Figure 35: Broadband beampatterns were captured using a 2 ms, 10-40 kHz, linear frequency modulated waveform.

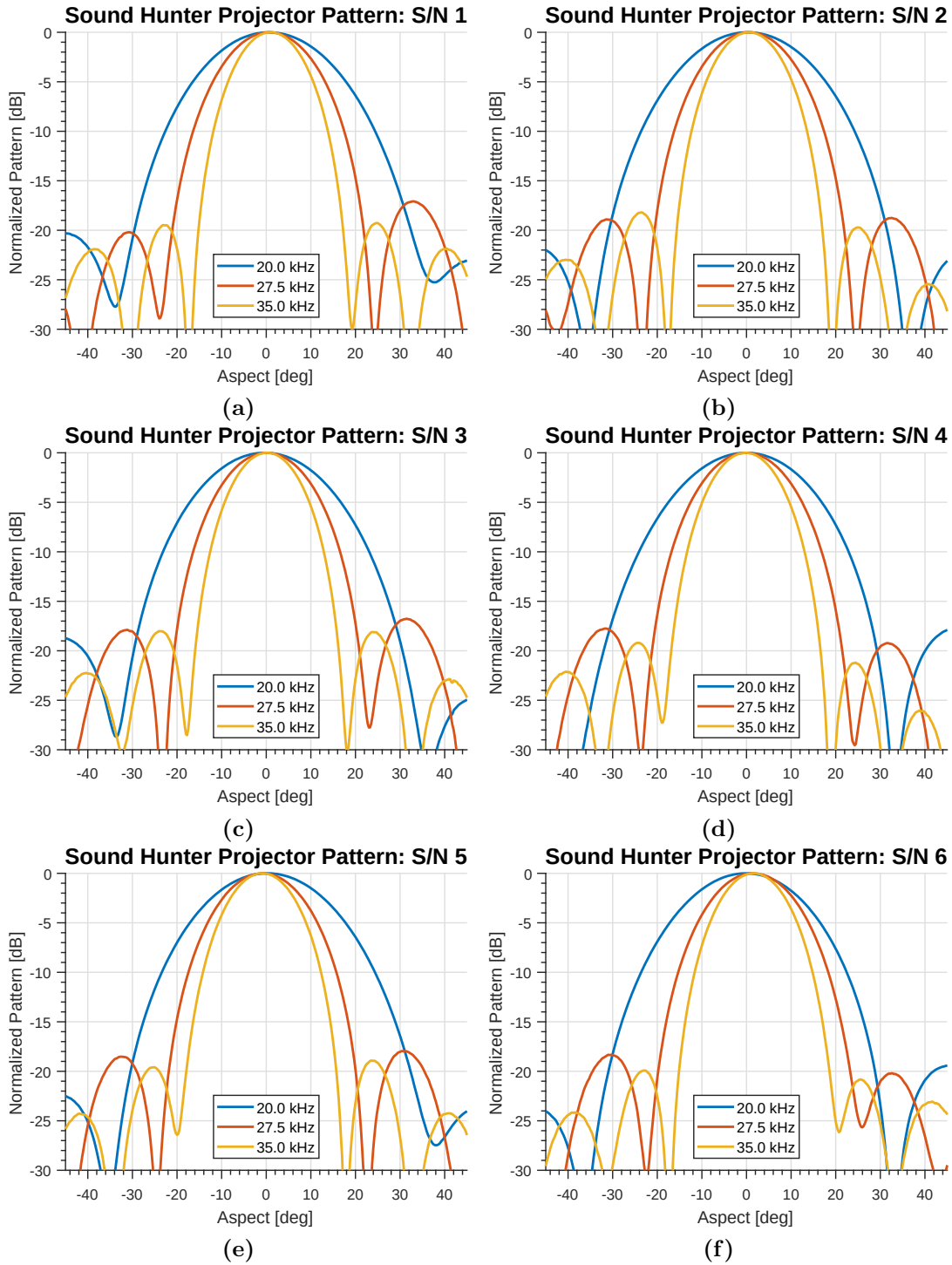


Figure 36: Beampatterns are shown for each of the six projectors fabricated for SVSS.

A.3 Hydrophone Calibration

The SVSS receive array consists of ten receiver modules each with eight channels. These modules were individually calibrated for both sensitivity (10-40 kHz) and beampattern (10-30 kHz). Horizontal and vertical beampatterns measured at 27.5 kHz are provided in Figure 37 for all eighty channels. The eight channel hydrophone modules are measured independently, and not integrated into the larger array configuration shown in Figure 5a. This difference will modify the baffling condition for most elements; therefore, the sidelobe structure seen here may not be an exact match for that seen in the field data. Similarly, this effect can be seen in the sidelobe structure deviations in Figure 37 because of the asymmetry in baffling for the individual hydrophone modules. Broadband beampatterns are shown for one eight channel module in Figure 38. These figures are available for the remaining 72 channels as well, but they have been omitted here for brevity. Finally, the on axis sensitivity is shown for all eighty channels in Figure 39. These tests show some spread in channel sensitivity; however, it is believed this is an artifact of the calibration procedure. The nature of the spreads seen here is similar to that seen when there is a misalignment between the reference projector maximum response axis and the hydrophone maximum response axis. In water tests have shown no sign of channel-to-channel variability in the sensitivity.

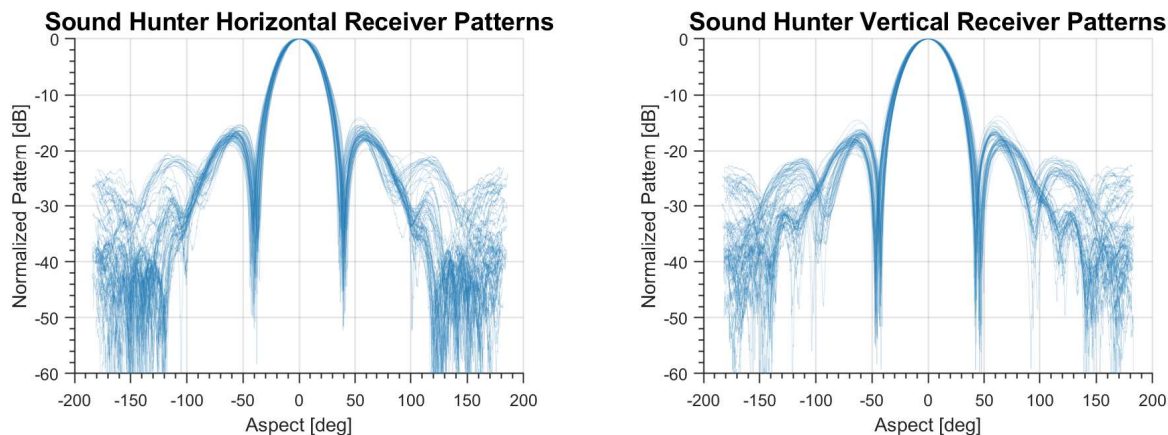


Figure 37: Horizontal (a) and vertical (b) beampatterns are measured at 27.5 kHz for all eighty receive channels.

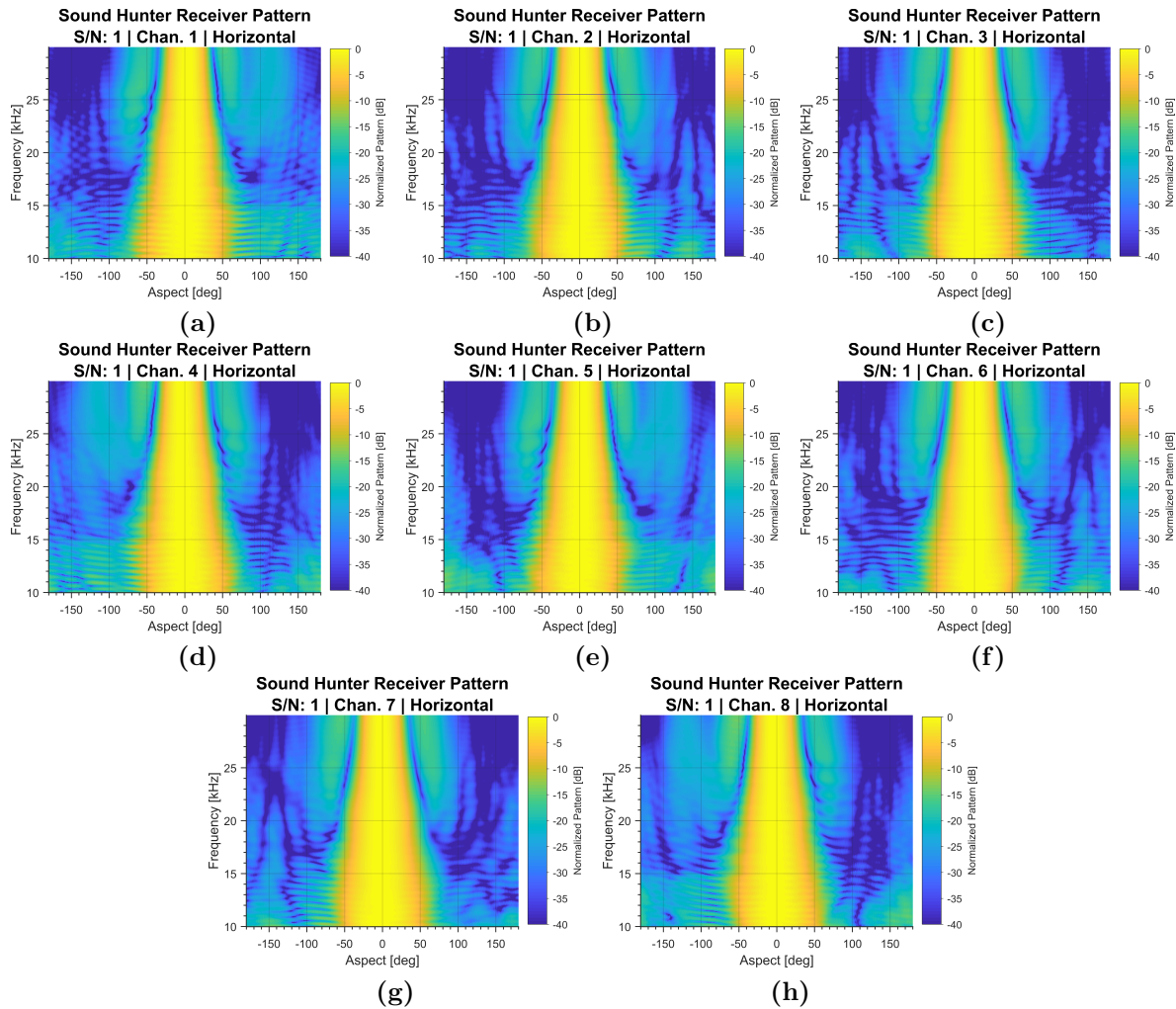


Figure 38: Broadband beampatterns were measured for all eighty receive channels. This figure provides those patterns for the first eight channels in the array.

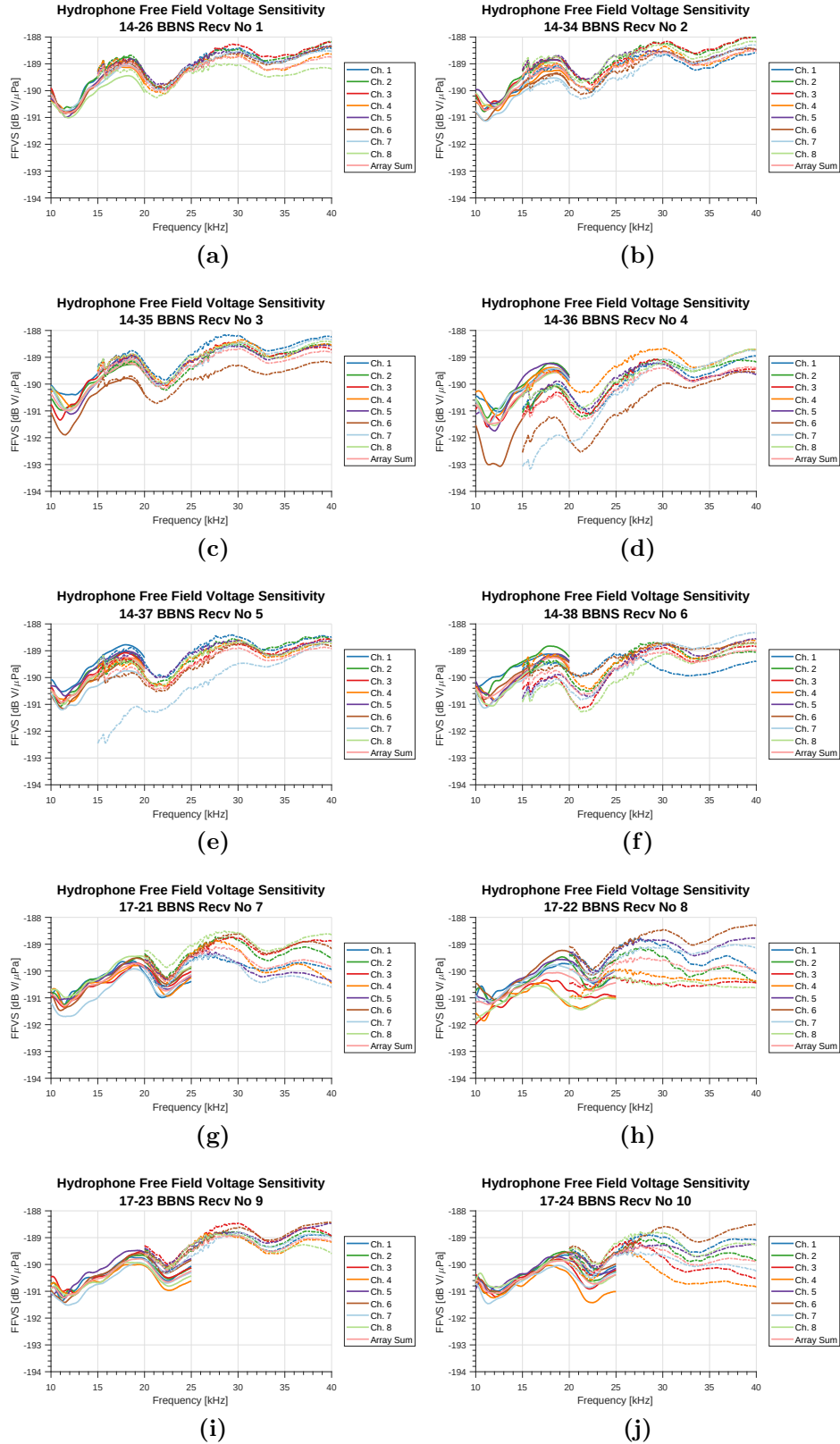


Figure 39: The FFVS was measured for all eighty receive channels.

B Cylindrical Target Images

The imagery of each of the observed cylindrical targets is provided in this appendix. Each target is called out by a designator with the format $\{D_T\#_D\#\}$ or $\{S_T\#_D\#\}$. The leading “D” and “S” indicate the deep and shallow fields, respectively. $\{T\#\}$ is the target number, where T2 is the short cylinder and T3 is the long cylinder. Finally, $\{D\#\}$ is the notional depth indicator. D0 indicates a surface target, D1 indicates a notional depth of 10 cm, and D2 indicates a notional depth of 15 cm.

A pair of figures is provided for each target. The left image is a depth slice selected to give the maximum target-to-background separability. The right figure shows three cross sections aligned at the target maximum response. The sensor trajectories were oriented so that the long axis of the cylinder is aligned with the target track. Therefore, the along-track cross section measures the target length and the cross-track cross section measures the target diameter.

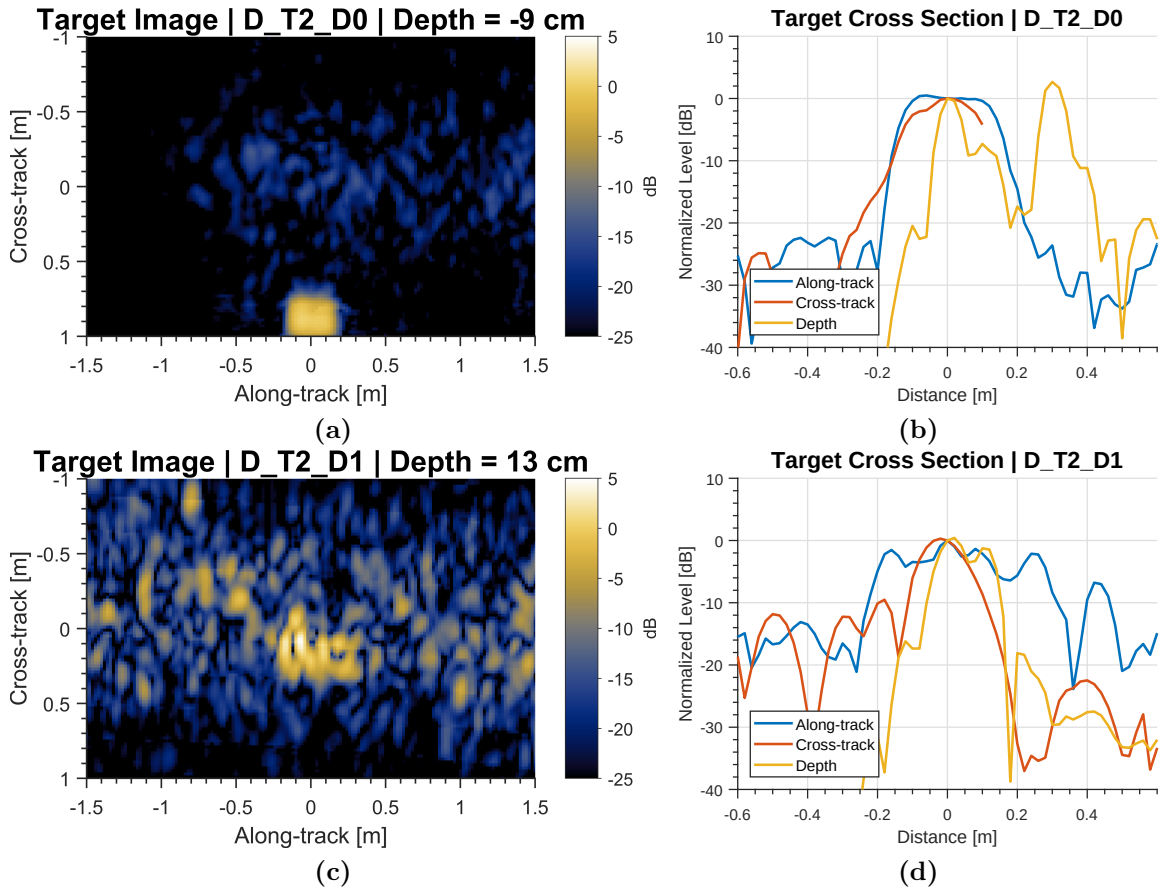


Figure 40: Imagery of the deep field short cylinder. The target is 31 cm long and 15 cm in diameter. The deepest buried short cylinder in the deep field was not visible in the acoustic imagery and is not included here.

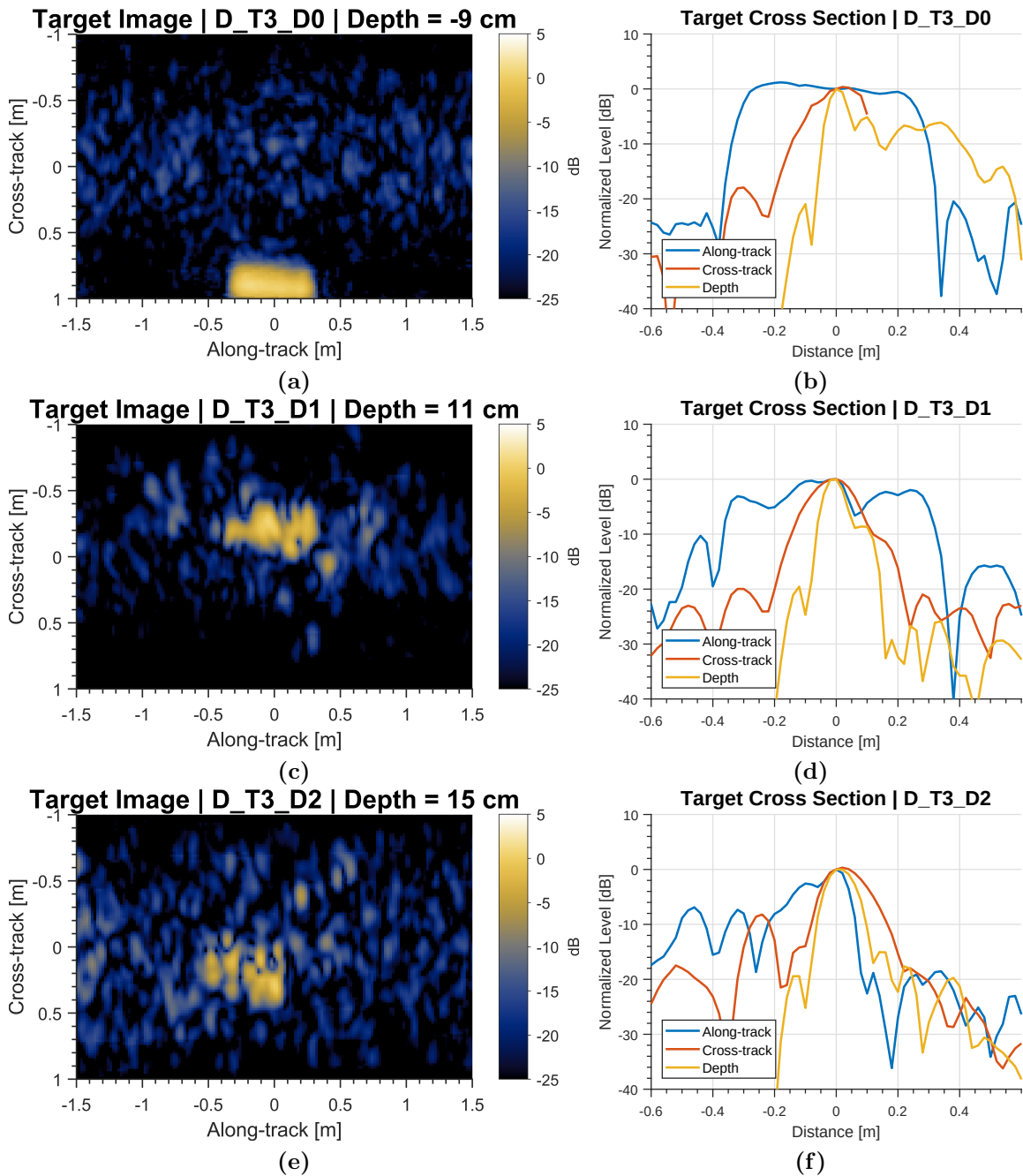


Figure 41: Imagery of the deep field long cylinder. The target is 61 cm long and 15 cm in diameter.

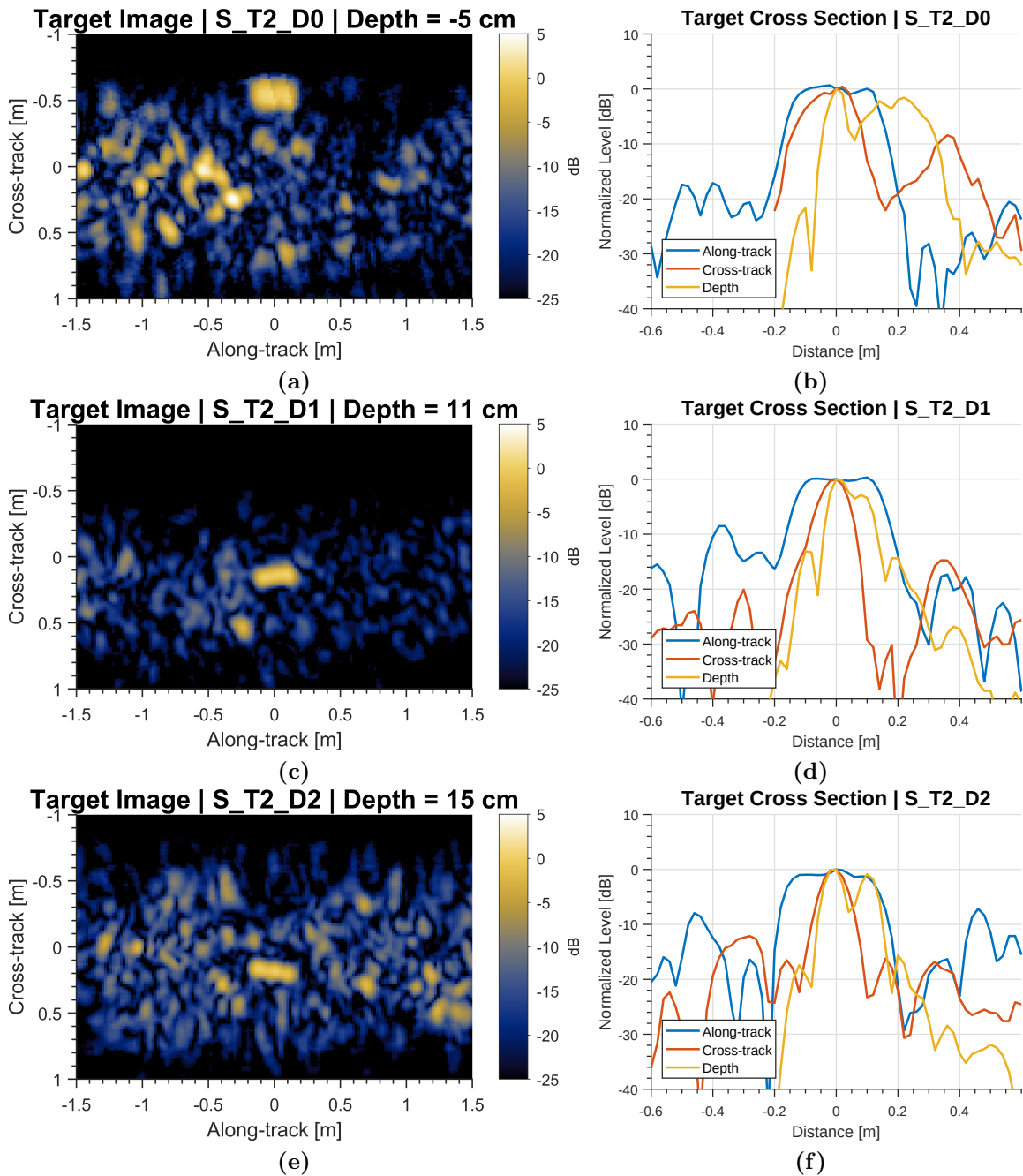


Figure 42: Imagery of the shallow field short cylinder. The target is 31 cm long and 15 cm in diameter.

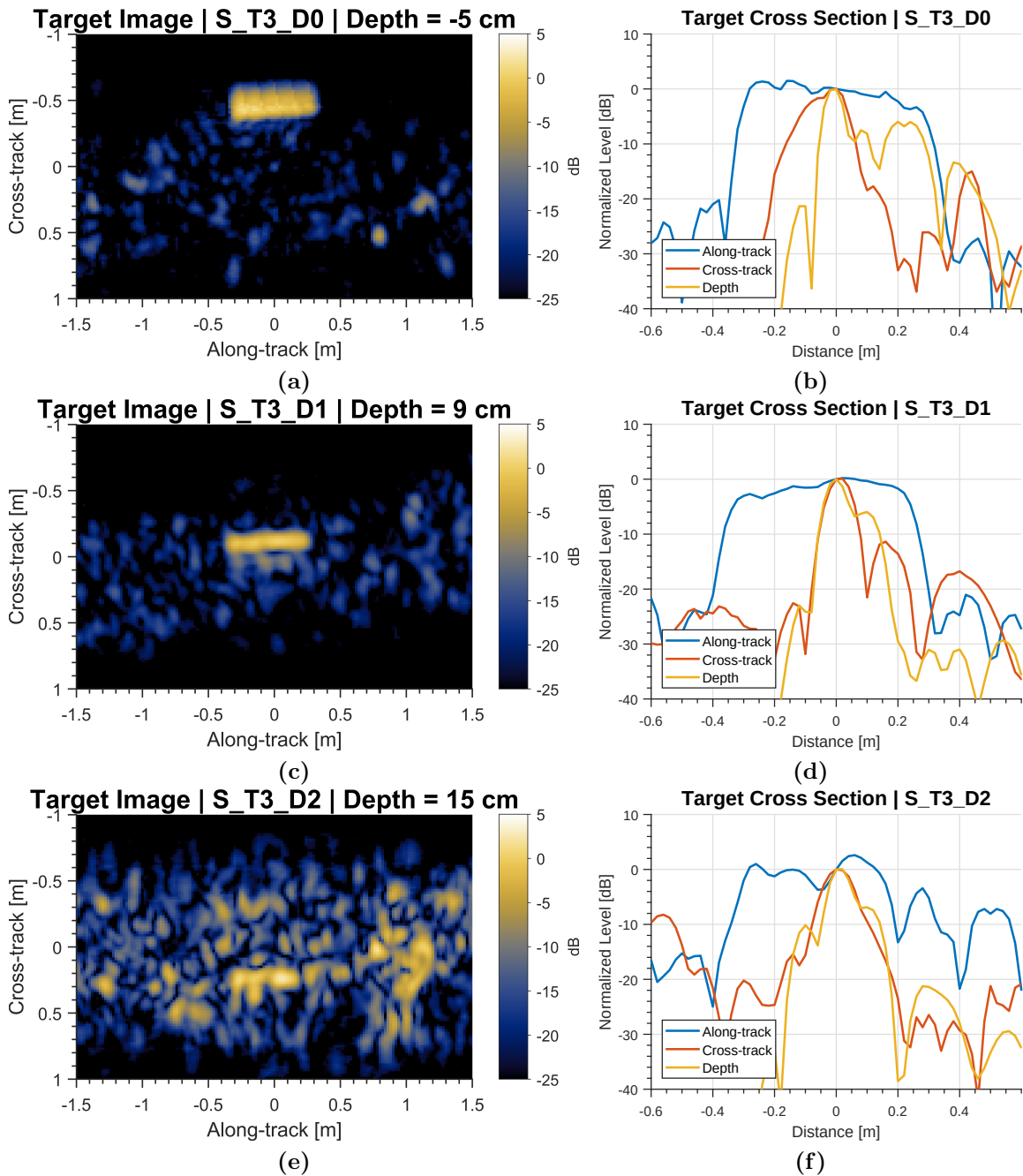


Figure 43: Imagery of the shallow field long cylinder. The target is 61 cm long and 15 cm in diameter.

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